

ABSTRACT OF THESIS

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Title of Thesis "STRUCTURAL ANALYSIS OF ROCKS DEFORMED BY FLOW : with special reference to the concept of symmetry".

Statistical structural analysis, as developed by Bruno Sander of Innsbrück, has been little used in Britain in study of rocks deformed by flow. This is particularly true of structural analysis on a microscopic scale which has come to be viewed as an introspective study generally unrelated to tectonic investigation on larger scales. Contributing to the incorrect perspective of this view of structural analysis, held by many structural geologists in Britain, has been an indifference to or an ignorance of the importance of statistical symmetry of fabric in kinematic analysis. To neglect of statistical symmetry can be traced the controversy which has in the past surrounded the recognition of "g- and B-lineations" in the rocks of the Scottish Highlands and the consequent suspicion of structural analysis present in the minds of many British structural geologists.

The first part of this Thesis consists of six papers (some of them describing studies made jointly with other structural geologists) concerned primarily with principles and techniques of structural analysis. The results of experimental deformation of dolomite rock are outlined and examples of A.V.A. are given. The fabrics of marbles from Greece are described and the geometry and dynamic interpretation of twin-lamellae produced in calcite by deformation are discussed. "Unrollable" and "non-unrollable" folds are described from the Scottish Highlands and a simple method of constructing structural block diagrams to scale is given. The geometry of internal rotation of passive structural surfaces is described in order to shew how differential behaviour of structural elements can affect symmetry of fabric and give an appearance of superposed deformation. In the last paper of the first part are summarized the writer's views on the significance of symmetry in tectonites. The concept of active and passive behaviour of structural elements is extended to structure on a large scale, and geometry and symmetry of structures produced by simple and superposed deformations are outlined. Fabric axes are defined for fabrics with monoclinic, triclinic and orthorhombic symmetry, and possible lines of kinematic and structural evolution in a uniformly stressed layered body are traced.

The second part of the thesis contains four papers in which structural analysis is used in regional studies. A pre-Carboniferous B-axis trending east-west is recognized in the Caledonian rocks of Vestspitsbergen. In the Basement System of Kenya, structural mapping of the Turoka area proves the structural geometry of the rocks to be different from that suggested by geologists of the Colonial Geological Survey. A kinematic interpretation of the geometry is suggested in terms of weakly developed $B \perp B'$ -tectonics. A summary is given of an incomplete investigation in the rocks surrounding Loch Leven in Argyllshire. The area is shewn to be one of $B \wedge B'$ -tectonics on a large scale. Some important conclusions bearing upon the age and nature of movements in the Moine thrust-zone, arising from a study made jointly with other geologists from the University of Edinburgh, are briefly described.

STRUCTURAL ANALYSIS of ROCKS DEFORMED by
FLOW: with special reference to the
concept of symmetry.

By

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INTRODUCTION.

Structural analysis, namely, the kinematic and dynamic interpretation of statistically determined structural geometry, is one of the youngest of the important branches of geological science. Its origin can be traced, perhaps, to several sources, but, without doubt, the most important of these is the unique genius of Professor Bruno Sander of Innsbrück, who remains today, as he began, on a somewhat lonely plane of understanding far removed from and all but inaccessible to most structural geologists. From Austria, the aims, principles and techniques of structural analysis have been very slow in spreading to the English-speaking world. To Mrs. E.B.Knopf must be given the credit for first introducing to the United States and Britain the elements of structural analysis on a microscopic scale (now, unfortunately, distinguished in those countries as "structural petrology") in a memoir of the Geological Society of America written jointly with Earl Ingerson (1938). This work remains today the most authoritative and faithful statement, in English, of Sander's views.

The most important development in the field of kinematic/

kinematic and dynamic interpretation of the microfabric of tectonites to have occurred outside Austria is, without doubt, the programme of experimental deformation of rocks begun by David Griggs, F.J. Turner and others of the University of California (Griggs and Miller, 1951; Handin and Griggs, 1951; Turner and Ch'ih, 1951; Griggs, Turner, Borg and Sosoka, 1951; Griggs, Turner, Borg and Sosoka, 1953; Borg and Turner, 1953; Turner, Griggs, Heard and Weiss, 1954; Turner, Griggs and Heard, 1954). This approach to problems of deformed rocks is very different from the approach made for the last forty years by Sander, but it is no less important; in a way, it is complementary to the studies of the Innsbrück school. Already, numerous papers have been published - as a direct outcome of the experimental work - in which kinematic and dynamic interpretations of the fabrics of naturally deformed rocks (especially of marbles and dolomite rocks) have been described, which would have been impossible on the basis of investigation of naturally deformed fabrics alone (see, for instance, Turner, 1953; McIntyre and Turner, 1953; Weiss, 1954a; Gilmour and Carman, 1954; Clark, 1954; Weiss, 1954b; Weiss, McIntyre and Kärsten, 1955; Weiss, 1955/

1955).

In Britain, application of techniques of structural analysis to problems of deformed rocks can be said to date from the publication in 1937 of F.C. Phillips' very important investigation of the microfabric of the Moine schists. Since that time, a handful of papers has appeared, mostly dealing with parts of the Scottish Highlands, in which techniques of structural analysis have been employed, generally to a small extent (for instance, Ritchey, 1947; Phillips, 1949; Wilson, 1950; McIntyre, 1951; Sutton and Watson, 1952; Flinn, 1952; McLachlan, 1953; Phemister and Williamson, 1954). To be grouped with these regional studies is a paper by E.M. Anderson (1948) which deals with the kinematic significance of linear structures in rocks deformed by flow; and, problems of the Norwegian Caledonides have been brought more sharply into focus for British readers by the publication in 1953 of a paper by Kvale in which parallels are drawn between structures in Scotland and Norway, and certain inferences are made.

These papers mark, in Britain, a slowly increasing awareness of the importance in tectonic investigations, both descriptive and interpretive, of the study/

study, on all scales, of the internal geometry of deformed rocks; but, reading through the papers cited above, a relatively impartial tectonician becomes aware that structural analysis has brought with it to Britain a degree of confusion. This confusion can be traced most surely to the impact upon an established view of structure and kinematics of demonstrations that this established view is inadequate to explain, completely, observable structural geometry. Phillips' was the first geometrical demonstration that the accepted view of structure and movement in the Moines was inadequate. This demonstration was made, unfortunately, on the smallest of tectonic scales, namely, the microscopic; but this was to be expected: it is generally much more difficult to make a convincing demonstration on a large scale than it is on a small scale because a large scale structure can never be directly examined in its entirety, whereas a single exposure, a hand specimen or a thin section can. This fact is locally responsible for the recognition in the deformed rocks of the Highlands of major structures which, although they are generally inferred, agree with accepted structural syntheses, and minor structures which, although they can be observed and even handled, perversely/

perversely refuse to do so. Perhaps if the first application of techniques of structural analysis to the rocks of the Highlands had been made on a larger scale, further application would have followed more quickly. As it was, field geologists, hypnotized by the strike of foliation, could not be expected to follow, immediately, difficult and alien techniques of structural analysis enclosed in an esoteric terminology in a foreign language, and performed with a piece of apparatus as rare and forbidding as a universal stage, especially when the results obtained were so at variance with those obtained from a study of major structures. At this time, also, was born in the minds of many British geologists the impression that structural analysis on a microscopic scale was something apart from structural geology and tectonics sensu lato, something only to be attempted by experts and not to be taken very seriously as a contribution to a study of structural geology. This impression has persisted until the present day, and it is very rarely in Britain that a paper is published in which microfabric analysis is used in a proper fashion as an integral part of structural analysis. It is not to be wondered, therefore, that structural/

structural analysis in Britain made little further headway until McIntyre (1951), in Strathspey, and Wilson (1953), in Strath Oyke, demonstrated the same geometrical relations, on respectively the megascopic and macroscopic scales, as Phillips had demonstrated on the microscopic scale. The way was then open for the re-examination of Highland tectonics that is now gathering momentum.

The controversy started as a result of Phillips' work is concerned largely with relations between linear structures, fabric axes and "directions of movement" (although what is moved where and in what fashion is rarely stated). No fully satisfactory definition of the fabric and kinematic axes - a, b(B) and c - defined by Sander exists in English for fabrics with different types of symmetry, and it is doubtful if, even today, the full significance of Sander's purpose in defining these axes has filtered through to the English-speaking world. There is no doubt that the significance of these axes has been imperfectly understood by some geologists who have attempted to recognize them in the rocks of the Scottish Highlands. To correlate lineations with "directions of movement" without first determining geometry and symmetry of strain can lead/

lead only to confusion and controversy.

With few exceptions (see Anderson in discussion of Elwell, 1955), most geologists in Britain are now agreed that many of the linear structures in the rocks of the Highlands, especially in the Moine schists, are parallel to "B-axes". For this agreement to become general has taken about twelve years from the date of publication of Phillips' initial study; twelve years to establish a view which, in many of the localities discussed in the controversy, could be established satisfactorily in a single afternoon. What was the reason for this protracted and rather futile controversy which is not completely disposed of at the present time? To the writer, it seems that misunderstandings can be traced to two main causes; first, to the use of terms and the application of concepts, derived from the writings of Sander, which have been rarely defined and, sometimes, imperfectly understood; and, second, to an underemphasis of the importance of symmetry of fabric in kinematic interpretation. The only structural geologists to have emphasized symmetry are Anderson and Kvale, and these, on what appear to be unsound grounds, have questioned the validity of "the principle of symmetry" (see/

(see page 117 of this thesis). Otherwise, structural geologists in Britain have been indifferent to fabric-symmetry of rocks deformed by flow, irrespective of the fact that it is the most important criterion in the determination of fabric axes.

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This thesis presents the results of some investigations of the fabrics of rocks deformed by flow made, on scales ranging from the microscopic to the megascopic, over a period of several years in a variety of geographical and tectonic environments. One of the investigations was made in conjunction with Professor F.J. Turner at the University of California, U.S.A: the remaining investigations were carried out from the University of Edinburgh. The ten separate papers, each one complete in itself, of which the thesis consists, fall into two definite groups; the first part of the thesis consists of six papers concerned, basically, with principles and techniques of structural analysis; the second part, containing four papers, is concerned with application of these principles and techniques to regional studies in Spitsbergen, Africa and Scotland. Important features of each paper are as follows:

Part/

Part I: The papers in this part are in a chronological order that corresponds also to the development of the writer's views on symmetry, as expressed in the last, most important, paper. Papers 1, 2, 3 and 5 are already published; paper 4 is in press. Paper 6 is to be prepared for publication at a later date.

1. Plastic Deformation of Dolomite Rock at 380°C: (jointly with F.J.Turner, D.Griggs and H.Heard); this investigation was made in 1953 at the University of California. The paper contains an example of A.V.A. (Achsenverteilungsanalysen - Ramsauer, 1941); this, together with another published by the writer (Weiss, 1954), constitutes the only examples of A.V.A. published outside Austria. Also of importance in this paper is the account of translation-gliding on $\{0001\}$ -planes and the resultant internal rotation of $\{02\bar{2}1\}$ -lamellae (L_g) in dolomite. These rotated lamellae now have been found in naturally deformed dolomite rocks by Mr. J.M.Christie of this Department, and are being used in studying the kinematics of the Moine thrust-zone (see paper 10).

2. Fabric Analysis of some Greek Marbles and its Application to Archaeology; this paper is included for the studies it contains of the fabrics of some marbles from Attica in Greece.
In/

In these are used the technique of dynamically interpreting patterns of $\{01\bar{1}2\}$ -twinning in calcite developed as a result of the experimental deformation of Yule Marble (see Turner, 1953). Also, some geometrical controls of these patterns arising from the geometry of twinning in calcite are discussed, and reference is made to "unrollable" and "non-unrollable" folds in Marble.

3. Contrasted Styles of Folding in the Rocks of Ord Ban, Mid-Strathspey (jointly with D.B.McIntyre and M.Kärsten);

A fold of quartzite is shown to have a homogeneous structural imprint, with orthorhombic symmetry, in its microfabric.

The quartzite, it is suggested, acquired a preferred orientation of quartz by cataclastic flow followed by recrystallization.

The fabrics of folded marbles and dolomite rocks are described and contrasted with the fabric of the quartzite.

4. Construction to Scale of Block Diagrams in Orthographic Projection (jointly with D.B.McIntyre); a method of preparing orthographic block diagrams of known scale in any direction is described. The term form-surface is introduced.

5. Fabric Analysis of a Triclinic Tectonite and its Bearing upon the Geometry of Flow in Rocks; the importance of this paper lies in its use of principles of internal rotation on a scale other/

other than an intragranular scale. It is shown that different structural elements can acquire different geometry and symmetry during a single deformation in a fashion decided by their structural behaviour. This is the first statement of the writer's views on active and passive behaviour of structural elements.

6. The Significance of Symmetry in Tectonites; this paper summarizes the writer's present views on the importance of symmetry in structural analysis. The concept of active and passive structural behaviour is extended to structural elements on a large scale; primary and secondary symmetry of fabric and S-active and S-passive flow are introduced. The geometry of complex and superposed strains is outlined.

Part II: papers 7 and 10 are already published, paper 8 is in the press and paper 9 is a preliminary summary of an uncompleted investigation.

7. Tectonic Features of the Hecla Hook formation to the South of St. Jonsfjord, Vestspitsbergen; this paper describes linear structures in the Caledonian metamorphic rocks of Spitsbergen, and demonstrates the existence of a pre-Carboniferous B-axis trending approximately east-west, normal to the/

the regional strike. A simple kinematic "unrolling" is used.

8. Structural Analysis of the Basement System at Turoka, Kenya; This long paper, written for the Colonial Geological Survey, outlines some principles of structural analysis and applies them to a study of the Basement System of southern Kenya. A few sections and diagrams from paper 6 are reproduced in this paper for the sake of completeness.
9. Structural Analysis at Loch Leven, Argyllshire; this is a very brief preliminary summary of the results of an investigation (still uncompleted) of the tectonics of the rocks to the north and south of Loch Leven. In the interests of brevity the full evidence for the conclusions drawn has not always been cited. An example of $B \wedge B'$ -tectonics on a large scale is described.
10. Appendix to "The Moine Thrust - its Discovery, Age and Tectonic Significance" by D.B.McIntyre (jointly with D.B.McIntyre and J.M.Christie); this brief appendix records some observations bearing on the kinematics of the Moine thrust.

The most important connecting thread of these papers is the emphasis which is throughout laid upon the study of statistical symmetry of fabric, so neglected in Britain. But the thesis is intended also to stress the essential/

essential unity of structures produced by flow in rocks, irrespective of scale. The term "structural petrology", used in Britain and U.S.A. to denote structural analysis on a microscopic scale, is, in the view of the writer, an unfortunate term which should be discarded. It makes an unnecessary distinction between study of structures on large and small scales and obscures the essentially homologous nature of structures in tectonites, irrespective of scale.

In most of the papers that form part of this thesis, references are made to the writings of Sander, in particular to his recent exhaustive treatise on the fabric of rock bodies (Sander, 1948 and 1950). The information contained in this great work is only very slowly becoming available to English-speaking structural geologists, mainly because of the great difficulties experienced by non-German readers in following Sander's written arguments. The writer cannot claim to be an exception to the general rule of ignorance of this work; but he has attempted to assimilate some of Sander's philosophy of a geometrical and "symmetrical" approach to structural analysis, although, as has happened in the past, it is possible that some of Sander's views/

views have been misinterpreted. For this reason, the writer must take full responsibility for the views which appear in the following papers under his name alone.

Advice and assistance received by the writer during the preparation of each part of this thesis are acknowledged individually in each paper; but the writer would like to record his especial indebtedness to Professor F.J.Turner of the University of California, Dr.D.B.McIntyre of Pomona College, California and Professor A.Holmes of the University of Edinburgh for assistance in a multitude of ways during the last few years. Thanks are due, also, to Martin Kärsten of Bonn, Germany, for much assistance in the study of German literature.

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THE
ROYAL EDWARD
SPECIAL

I. PRINCIPLES and TECHNIQUES of STRUCTURAL
ANALYSIS.

I. 1. Plastic Deformation of Dolomite Rock
at 380°C.

(Jointly with F.J.Turner, D.Griggs
and H.Heard)

[AMERICAN JOURNAL OF SCIENCE, VOL. 252, AUGUST 1954, PP. 477-488]

PLASTIC DEFORMATION OF DOLOMITE ROCK AT 380°C.

FRANCIS J. TURNER, DAVID T. GRIGGS, HUGH HEARD,
AND LIONEL W. WEISS

ABSTRACT. A cylinder of dolomite rock from Dover Plains, New York was compressed 9.4 percent at 380°C., 3000 atmospheres confining pressure. Deformation was plastic; but the dolomite rock is less ductile and three times as strong as Yule marble deformed under comparable conditions.

Fabric analysis shows a rather weak pattern of preferred orientation of c and of a crystal axes prior to deformation. This is somewhat modified in the deformed rock, but reorientation has not proceeded far enough to give a pattern symmetrically related to the system of applied stress. Before and after deformation the fabric is essentially homogeneous within the field of a thin section. Two mechanisms of plastic deformation have been demonstrated: (1) twin gliding on {0221}, the sense of shear being such that upper layers of the crystal lattice are displaced downwards from the upper end of the c axis; (2) translation gliding on {0001}, with the a axes as probable glide directions.

INTRODUCTION

A block of almost pure dolomite rock of lower Cambrian age, collected by Mr. G. V. Carroll from South Dover quarry, Dover Plains, New York has been selected for experimental deformation. This paper records its behavior when deformed dry at 380°C. under a confining pressure of 3000 atmospheres. Detailed analyses of the microscopic fabric before and after deformation, with special reference to preferred orientation of the component crystals, are presented; and from these certain inferences are drawn regarding the mechanism of gliding in the dolomite crystal lattice.

EXPERIMENTAL WORK

A cylinder cut normal to the 5 plane (fig. 1) was compressed 9.4 percent at 380°C., 3000 atmospheres confining pressure, dry. The apparatus, procedure, and method of reduction of the data are described elsewhere (e. g. Griggs, Turner, Borg, and Sosoka, 1953). The stress-strain curve is shown

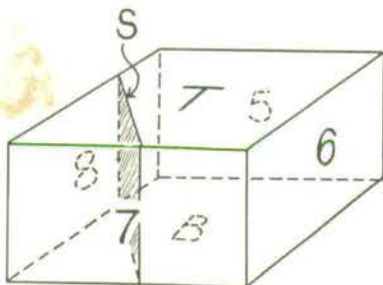


Fig. 1. Block of Dover Plains dolomite showing mutual relations of numbered faces and color-banding S.

in figure 2. When the stress began to drop, indicating the onset of shearing fracture, the load on the specimen was released. The specimen was recovered whole, with no evident macroscopic shear. The jacket was not broken. The thin section shows grain separation which suggests that intergranular cohesion was being reduced by a process of distributed shear. One other experiment on Dover Plains dolomite has been performed—a T cylinder deformed

at 300°C., 5000 atmospheres pressure. This specimen was 15 percent stronger than the 5 cylinder at 380°C. It failed by shearing fracture after 11.5 percent total strain.

These two experiments are very similar to those done by Dr. J. W. Handin at the Shell Laboratories in Houston, in which Hasmark dolomite was used. Although the Hasmark rock has quite a different fabric from that of the Dover Plains dolomite, Handin's stress-strain curves for 300°C., 5000 atmospheres are nearly identical with ours, and shearing failure occurred after about the same total strain. Our experiments were exploratory in nature, testing whether the Dover Plains dolomite had similar properties to those of the Hasmark rock.

In our experience at 300°C., 5000 atmospheres, and at 380°C., 3000 atmospheres, dolomite is not as ductile as marble and it is roughly three times as strong. Dolomite is weaker by a factor of two and is more plastic than either basalt or granite under these same conditions.

RESULTS OF PETROFABRIC ANALYSIS

Fabric of original rock.—The Dover Plains rock consists almost entirely of dolomite. Calcite is completely absent, and colorless mica and quartz are minor impurities. No foliation or lineation is visible either in hand specimen or in thin section, but there are traces of color banding (S in figure 1) normal to the T surface of the block. Grains tend to be equant and sharply bounded by nearly plane surfaces few of which, however, approximate to simple crystallographic planes. Most grains have mean diameters between 0.2 mm and 1 mm.

The optic axis of a dolomite grain is readily located by direct measurement with a universal stage,¹ so that analysis of the fabric is a much less lengthy procedure than is the case with even-grained calcite marbles where it is commonly necessary to measure a series of ordinary ray directions to locate the *c* axis of a calcite grain. Lamellae are conspicuous but rather sparsely developed (pl. 1A). They invariably are parallel to $\{02\bar{2}1\} = f$, and seldom are thick enough to allow optical identification as twinned structures. Most grains carry only one or two sets of lamellae. Characteristically they are so sharply defined that the observed angle *f* to *c* is within one or two degrees of the true value, $62\frac{1}{2}^\circ$.

Preferred orientation of the dolomite lattice in the undeformed rock is recorded in the four orientation diagrams of figure 3. A plot of 150 *c* axes measured in three traverses across a single thin section brings out the essential pattern (fig. 3A)—a girdle within which there is a broad arc of concentration in the upper-right and lower-left quadrants. The pattern is confirmed by a diagram (fig. 3B) based on 500 *c* axes in the same section, and a high degree of homogeneity of fabric within the field of one thin section is thus established. The girdle axis is normal to T and so lies in the plane of color banding, S. The optic axes tend to be orientated at rather high angles to S.

¹ If hemispheres of refractive index 1.649 are used, no correction of tilt is necessary provided both the *c* axis and *f* lamellae are located by bringing them parallel to the E-W rotation axis of the universal stage.

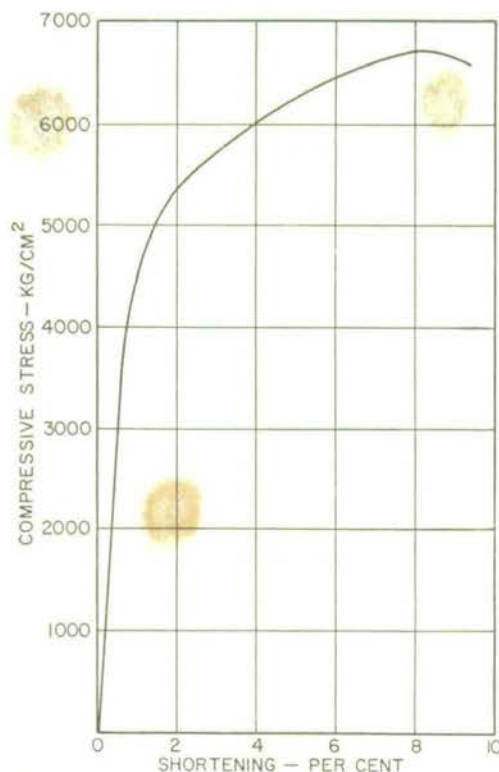


Fig. 2. Stress-strain curve for 5 cylinder of Dover Plains dolomite (specimen 403), compressed 9.4% at 380°C., 3000 atmospheres confining pressure, dry.

The three a axes in each of 100 grains, selected at random from those of figure 3A, were measured and plotted in figure 3C. This shows three maxima 60° apart on a great circle, suggesting some preferred orientation of a as well as of c . This is confirmed by plotting (in fig. 3D) the a axes of 19 grains whose c axes lie within 20° of the normal to the great circle containing the 3 maxima of figure 3C. In figure 3D there is marked clustering of axial points around the general a -axis maxima, and in 7 grains coincidence of all three a axes (crosses) is exact.

Figure 4E shows a plot of all conspicuous {0221} lamellae (112 lamellae measured in 100 grains). The blank central area constitutes a "blind spot" within which would lie the poles of lamellae inclined at low angles to the section and consequently inaccessible to observation. Taking this into account, there seems to be no significant pattern of preferred orientation of {0221} lamellae.

Fabric of the deformed rock.—The microscopic appearance of a T section of specimen 403 (5 cylinder, shortened 9.4%) is shown in plate 1B. The most obvious result of deformation is a general increase in development of {0221} lamellae which may be so abundant as to render individual grains semiopaque in ordinary light. In a number of grains coarse parting has developed approximately parallel to {1120}. There seems also to be a faint

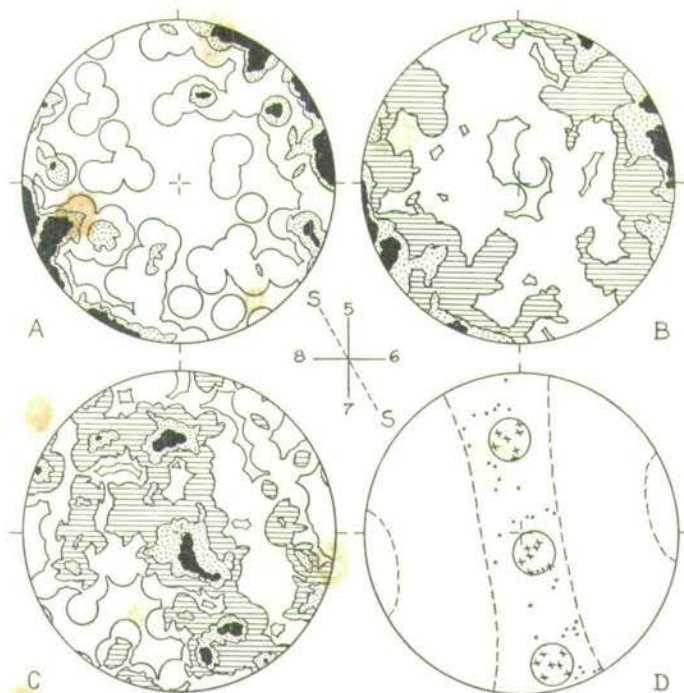


Fig. 3. Orientation diagrams, undeformed Dover Plains dolomite, T section.

- A. c axes in 150 grains. Contours 3%, 2%, 0.7% per 1% area.
- B. c axes in 500 grains, including those of A. Contours 3%, 2%, 1%, 0.2% per 1% area.
- C. a axes, 300 in 100 grains. Contours 3%, 2%, 1%, 0.3% per 1% area.
- D. a axes in 19 grains whose c axes fall in the area bounded by the small circle at the east and west margins. Crosses show grains whose three a axes all fall within the circular areas corresponding to the maxima of diagram C.

tendency for reduction in average grain size and for slight elongation of grains parallel to the NE-SW diagonal of the photograph.

In figure 4, orientation diagrams for c axes (B), a axes (D) and conspicuous $\{02\bar{2}1\}$ lamellae (F) are compared with corresponding diagrams (A, C, E) for the undeformed dolomite. The initial orientation pattern of the lattice has been modified in two ways: (1) the concentration of c axes has been condensed and displaced counterclockwise so that the mean inclination of c axes to the axis of compression is somewhat reduced; (2) the a -axis pattern of figure 4C has been partially obliterated. Neither the c -axis nor the a -axis diagram is symmetrically related to the axis of compression. A plot of 485 c axes (fig. 5A) brings out the state of preferred orientation of c axes more clearly than does the 100-grain sample shown in figure 4B.

Prominent $\{02\bar{2}1\}$ lamellae in the deformed dolomite show almost random orientation, with a slight tendency for concentration at high rather than at low angles to the compressive force (fig. 4F).

Homogeneity of fabric.—From the close similarity between c -axis diagrams for 100-150 grains and for 500 grains measured in the same section,

the fabrics of the undeformed and deformed rocks appear to be essentially homogeneous within the field of a single thin section. This conclusion is confirmed by analyzing the distribution of *c*-axes of various orientations within

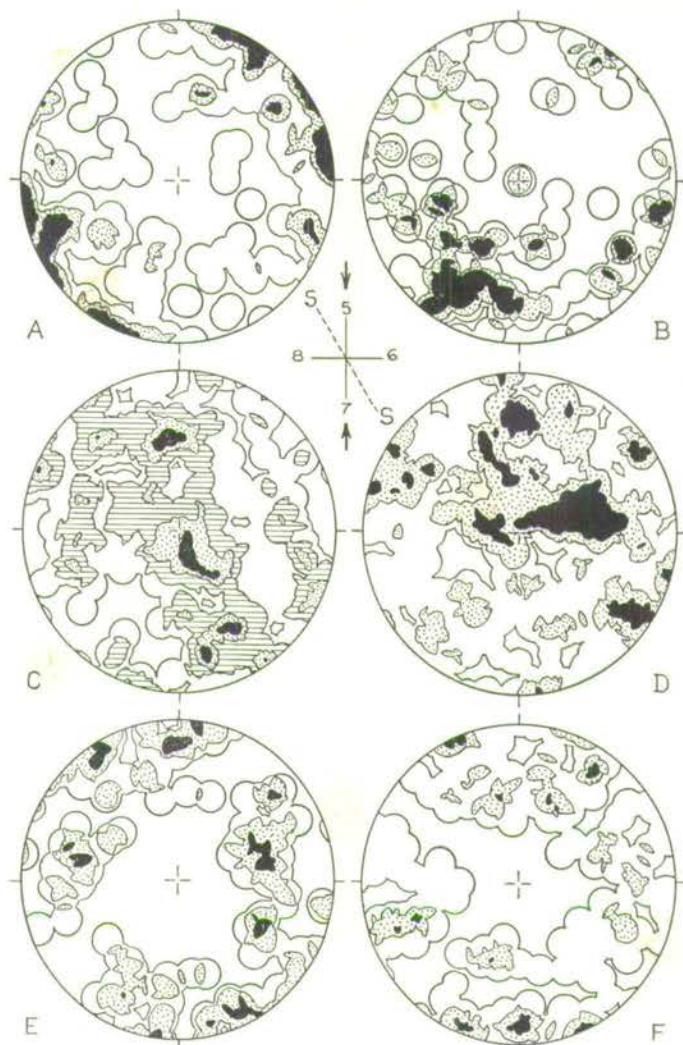


Fig. 4. Orientation diagrams for undeformed (A, C, E) and deformed Dover Plains dolomite (B, D, F). Deformed specimen (403) was shortened 9.4% in direction shown by arrows.

- A. *c* axes in 150 grains. Contours 3%, 2%, 0.7% per 1% area.
- B. *c* axes in 100 grains. Contours 3%, 2%, 1% per 1% area.
- C, D. *a* axes, 300 in 100 grains. Contours 3%, 2%, 1% (in C only), 0.3% per 1% area.
- E. Conspicuous {0221} lamellae, 110 in 100 grains. Contours 4%, 2%, 1% per 1% area. Note central "blind spot."
- F. Conspicuous {0221} lamellae, 142 in 100 grains. Contours 3.3%, 2%, 0.7% per 1% area. Note central "blind spot."

a particular field, according to the method described by Ramsauer (1941) and Sander (1950, p. 161-192) as *Achsenverteilungsanalyse* or *A. V. A.* The c axes of all grains within the area photographed in plate 1A (undeformed dolomite) are first measured. The grains are next divided into five groups according to orientation of c axes. Two of the orientation groups correspond to the two sectors of axial concentration in figure 3B, and the other three are arbitrarily defined. On a tracing of the photograph (pl. 1C) the grains of each group are marked by a distinctive symbol, so that any tendency for grouping of similarly oriented grains in space becomes obvious.² Little or no such grouping is apparent in plate 1C. In a corresponding area of the deformed dolomite (pl. 1B, D) the fabric is still essentially homogeneous except possibly for a slight tendency for similarly oriented grains to be aligned parallel to the NE-SW diagonal.

MECHANISM OF GLIDING IN DOLOMITE

Previous ideas.—Johnsen (1902) recorded experimental evidence that dolomite crystals deform plastically by gliding on $\{0001\} = c$, parallel to an a axis. From petrofabric analysis of natural dolomite fabrics, Fairbairn and Hawkes (1941) concluded that dolomite may also deform by twin gliding on $\{02\bar{2}1\} = f$, the sense of shear being such that upper layers of the lattice are displaced downward from the c axis (elsewhere we have designated this sense of movement *negative* as contrasted with *positive* sense of twin gliding on $\{01\bar{1}2\}$ in calcite). The same two mechanisms have been invoked by Bradley, Burst and Graf (1953) to explain the observed effects of progressive grinding on thermal and X-ray properties of powdered dolomite. More recently still Handin and Fairbairn (1953) have produced f twinning in dolomite in the laboratory at 300°C., and have confirmed the conclusion of Fairbairn and Hawkes that the sense of shear is negative.³

New evidence of twin gliding on $\{02\bar{2}1\}$.—In experimentally deformed Dover Plains dolomite conspicuous lamellar twinning on $\{02\bar{2}1\}$ appears in about 15 percent of the grains—usually in one, sometimes in two sets per grain. Many other grains have one or two very thin but still distinctly twinned f lamellae, associated with more numerous lamellae that are too thin to be optically recognized as twins. For any twin lamella the sense of shear with reference to the axis of compression is obvious. But the sense in relation to crystallographic coordinates such as the c axis can be determined only if it is known which of the two lattices in the grain is the original and which the newly twinned lattice. Converging evidence from four independent sources bears on this problem:

(1) In any grain with one set of lamellae there is a predominating "host lattice," and a "lamella lattice" which in aggregate makes up but a minor fraction of the total volume of the grain. Absence of half-twinned grains makes it improbable that the majority of the grains with f lamellae are in fact approaching a completely twinned condition. The probable alternative

² The critical reader is advised to color each orientation group of plate 1C and D distinctively in order better to evaluate the homogeneity of the fabric.

³ Personal communication, November, 1953.

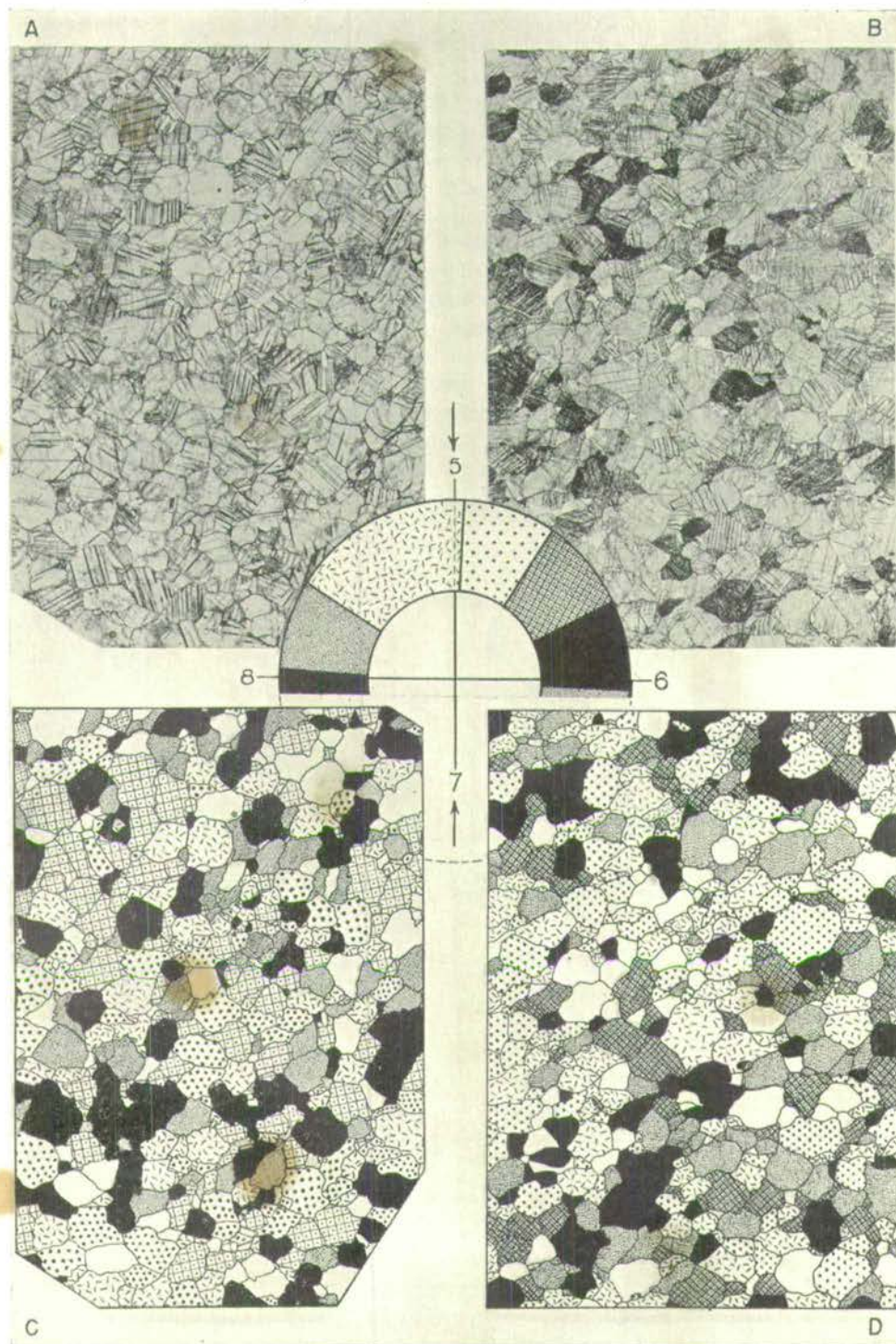


PLATE 1

Photomicrographs (X 7) of T sections of Dover Plains dolomite before deformation (A) and after deformation (B). Distribution of grains of various orientations in the photographed areas is shown in C (before deformation) and D (after deformation). Orientation of optic axes in C and D corresponds to the 6 divisions of the inset projection.

is that the host lattice is original, and the lamella lattice is the result of twin gliding.

(2) Where two sets of f lamellae are present in one grain, the lattice to which both f planes belong must be original. This is invariably the host lattice.

(3) The orientation of c axes in 485 grains in the deformed rock is shown in figure 5A, which combines the data of two selective diagrams: figure 5B, 407 grains in which recognizable $\{02\bar{2}1\}$ twins are absent or insignificant; and figure 5C, host lattices of 78 grains with obvious $\{02\bar{2}1\}$ twinning. The complementary nature of figures 5B and C is readily explained on the assumption that the host lattices of the twinned grains are the original lattices; for twinning would then have developed only in grains of one orientation, and almost every grain so oriented would have twinned. Moreover the observed slight reorienting of grains that are subparallel to the compression axis would be compatible with the relatively low degree of deformation of the specimen. (The percentage of grains having the c axis inclined at 25° or less to the compression is 12% before, and 9% after deformation.) On the other hand, two highly improbable implications arise if the host lattices of figure

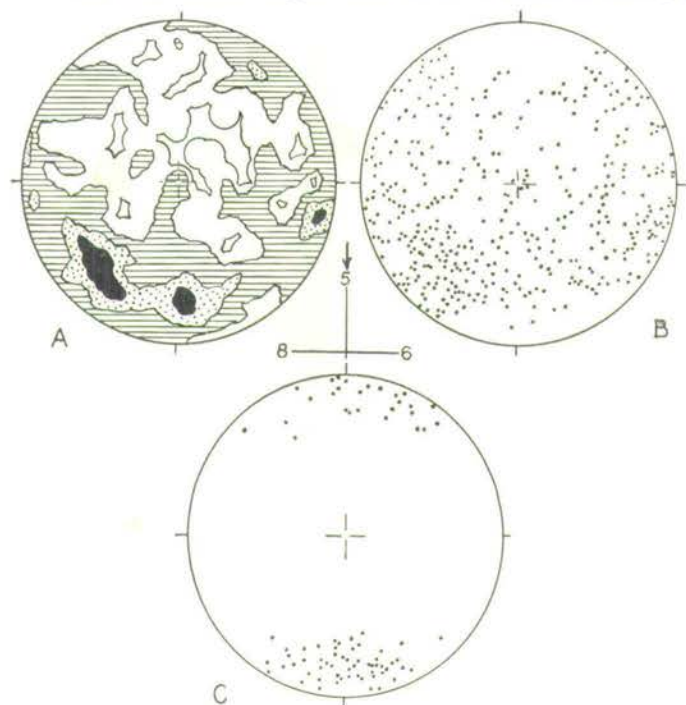


Fig. 5. Orientation diagrams for deformed Dover Plains dolomite, specimen 403 shortened 9.4% in direction of arrow.

- A. c axes in 485 grains. Contours 3%, 2%, 1%, 0.2% per 1% area.
- B. c axes in 407 grains showing little or no $\{02\bar{2}1\}$ twinning.
- C. c axes in 78 grains showing obvious $\{02\bar{2}1\}$ twinning.

5C are interpreted as products of twinning: first that 78 grains whose c axes initially were inclined at 50° - 90° to the compression axis twinned almost

completely, while many other grains of similar orientation (in fig. 5B) remained untwinned; and secondly that some 60 grains whose c axes initially were inclined at 25° or less to the compression axis have become completely reoriented by some means not involving twinning.

(4) In calcite we have found that when the lattice becomes completely twinned on an $\{01\bar{1}2\}$ plane e_1 , a pre-existing lamella e_2 of different orientation rotates internally through the lattice to a new orientation L_3 that can be predicted from the geometry of twinning (Borg and Turner, 1953, p. 1349; Turner, Griggs and Heard, 1954). Similarly a pre-existing $\{02\bar{2}1\}$ lamella f_2 in dolomite will rotate internally to a new orientation during twin gliding on f_1 . And this new orientation can be computed from the geometry and sense of twinning on $\{02\bar{2}1\}$. It can be shown that if shear on f_1 is negative, an original f_2 lamella rotates internally through 21° and so comes to coincide with f_2 of the twinned lattice (f'_2 in fig. 6B). If shear on f_1 were positive the angle of rotation in the opposite sense would be 28° and the

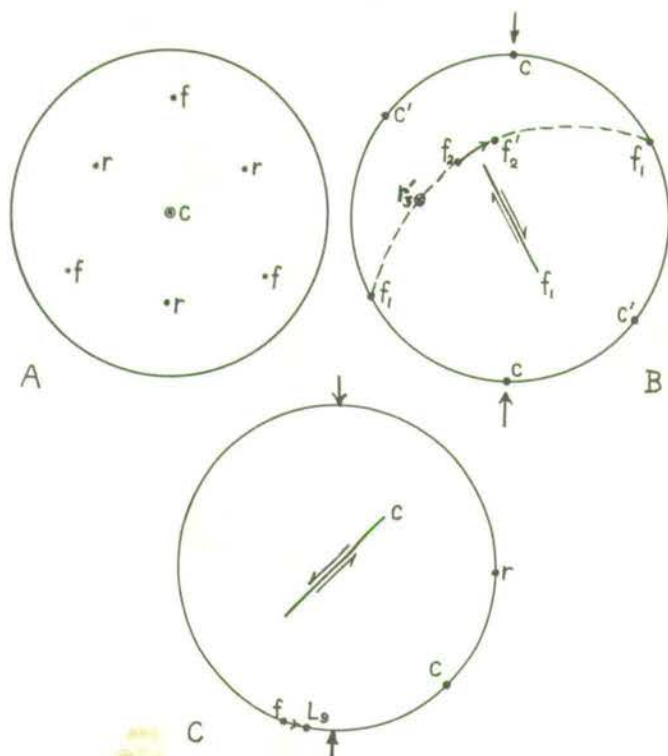


Fig. 6. Equal-area projections for dolomite.

- A. Mutual relations of $\{10\bar{1}1\} = r$, $\{02\bar{2}1\} = f$, and c axis.
- B. Twin gliding on f_1 induced by vertical compression. c , f_1 and f_2 are in original lattice; c' , r'_3 and f'_2 are in twinned lattice. Internal rotation of f_2 to f'_2 corresponds to the sense of shear on f_1 indicated by arrows. Shear in the opposite sense would rotate f_2 to r'_3 .
- C. Internal rotation of f to L_3 , explained by translation on $\{0001\} = c$ in the sense shown.

ultimate position of the rotated f_2 structure would coincide with r_3 of the twinned lattice (r'_3 in figure 6B). We have measured a number of dolomite grains in which an early set of f_2 twin lamellae are deflected within broad f_1 lamellae of later origin. In every instance the deflected lamella is parallel to f_2 of the lattice formed by twinning on f_1 . The sense of shear on f_1 must be negative.

We conclude that the sense of shear for twinning on $\{02\bar{2}1\}$ is negative (fig. 6B), and that conspicuous twinning is restricted to grains whose c axes were originally inclined to the axis of compression at angles between zero and 25° (fig. 5C). The observed tendency for slight outward migration of c axes from the immediate vicinity of the axis of compression is attributed to external rotation of grains through a few degrees in the sense opposite to that of twin gliding.

New evidence of translation gliding.—In dolomite, as in calcite, the most satisfactory evidence of translation gliding is provided by lamellae of anomalous crystallographic orientation (Turner, Griggs and Heard, 1954). These can be identified, in dolomite, as early-formed $\{02\bar{2}1\}$ lamellae that have been internally rotated through the grain to their present anomalous orientation, in the course of translation gliding on some steeply intersecting invisible glide plane. Since the axis of internal rotation is the intersection of the glide plane and the rotated lamella, the pole of the glide plane on a projection must lie on the same great circle as the poles of the lamella, respectively before and after rotation. Choice of a glide plane is further limited by two additional requirements: the observed sense of rotation must conform to the requirements of the system of applied stress, and the coefficient of resolved shear stress, S_0 , for the postulated glide system must be high. The problem, then, is to find a crystallographic glide system that satisfactorily accounts for the internal rotation of $\{02\bar{2}1\}$ lamellae in a number of differently oriented grains in a given specimen.

In the deformed specimen of Dover Plains dolomite numerous grains have a set of lamellae, which we designate L_0 , intersecting rational $\{02\bar{2}1\}$ lamellae, f_1 , at 6° - 10° . Fortunately it is possible to locate the c axis and both f_1 and L_0 lamellae within about 1° , so that the direction and sense of internal rotation may be determined satisfactorily in most grains.

Figure 6C illustrates an ideal orientation to which most grains with L_0 lamellae closely approximate. The planes f_1 , L_0 , and $\{0001\} = c$ are cozoal. The pole of L_0 lies between those of f_1 and c and is 6° - 10° from the pole of f_1 . The pole of c is 40° - 50° from the axis of compression. Gliding on c parallel to one of the a axes completely accounts for all these conditions, for S_0 has a value of 0.4-0.5, and the sense of observed rotation accords with that demanded by the orientation of c in relation to the axis of stress. No other glide system satisfies the requirements imposed by the observed data of rotation. We conclude that grains with L_0 lamellae have deformed by gliding on $\{0001\} = c$, with one of the a axes as probable glide line.

To test this conclusion, assuming translation on $\{0001\}$ parallel to a , we now compute the shortening, ϵ , of grains with L_0 lamellae, from the equation

$$\cot \alpha - \cot \beta = \frac{\epsilon}{S_0} \sin \gamma,$$

where α = angle L_9 to c = $52\frac{1}{2}^\circ - 56\frac{1}{2}^\circ$,

β = angle f_1 to c = $62\frac{1}{2}^\circ$,

γ = angle a_1 (glide line) to a_2 (rotation axis) = 60° ,

and $S_0 = 0.4 - 0.5$.

From this, ϵ is computed as 7%-14%, a range of values which accords with the mean of 9.4% for the specimen as a whole.

The above discussion applies to the great majority of grains with anomalous lamellae. There are a few grains, however, where the observed data of rotation are inconsistent with gliding on {0001}. It is not certain whether these rare discrepancies indicate some other mechanism of gliding or merely lack of precision in measurement. Further consideration must await future experiments in which it is hoped to achieve strains high enough to resolve such ambiguities.

CONCLUSIONS

(1) Dolomite rock compressed at 380°C. and 3000 atmospheres has been plastically deformed to give a permanent shortening of 9.4 percent. The rock is less ductile but three times as strong as Yule marble deformed under comparable conditions.

(2) One of the mechanisms of plastic deformation in dolomite is twin gliding on {0221}, the normal to the intersection with {0001} being the direction of gliding. The sense of shear is negative, i.e., upper layers of the lattice are displaced downward away from the c axis.

(3) A second and perhaps more important mechanism is translation gliding on {0001}, probably parallel to one of the three a axes. This leaves no trace of visible {0001} lamellae in thin sections; but it causes internal rotation of pre-existing {0221} lamellae to an anomalous orientation L_9 , such that the angle L_9 to {0001} is less than the angle {0221} to {0001}.

(4) Shortening of a cylinder of dolomite rock by 9.4 percent leads to slight changes in the pattern of preferred orientation of the c axes, consistent with plastic deformation of grains by the two mechanisms just mentioned.

ACKNOWLEDGMENTS

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⁴ Contract Nonr — 222(08), Project NR 081 134.

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FABRIC ANALYSIS OF SOME GREEK MARBLES AND ITS APPLICATIONS TO ARCHEOLOGY

L. E. WEISS

ABSTRACT. It is suggested that petrofabric analysis may assist in the restoration of fragmentary inscriptions and works of art made of marble. Petrofabric principles which may be of importance are discussed, and a method of preparing "fabric pictures" summarizing distinctive features of the fabric of individual specimens of marble is outlined. Seven specimens of marble from quarries in Greece are analyzed in this way, and it is concluded that distinctive fabric pictures will be obtained from most marbles. Procedure in applying these techniques to specific problems is demonstrated for hypothetical examples.

THE PROBLEM

In a recent paper Herz and Pritchett (1953) have demonstrated to students of Attic epigraphy the importance of describing specimens of marble in the systematic manner used by petrologists. Epigraphists, and most archeologists, use unsatisfactory petrographic terms to describe fragments of marble; and a definite locality of origin for individual specimens of marble is commonly assigned on the basis of a superficial examination of color and general appearance. Herz and Pritchett state that color alone is not a criterion of the place of origin of a marble; the quarries in Attica which they have examined show that there is a considerable variation in the color and texture of the marble within any one quarried mass. A more complete descriptive analysis using not only color but grain size, composition (accessory minerals present), and orientation of foliation¹ and lineation is suggested. Examination of these features in two or more fragments of marble in many instances will give sufficient information to enable one fragment to be related to another. By examining the orientation of linear structure in two specimens of marble previously supposed to have formed part of one stele, Herz and Pritchett successfully demonstrated that these fragments could not have formed part of one block of marble (1953, p. 81-83), thereby solving an archeological problem.

Careful study of immediately visible features of fragments of most marbles will indicate readily whether or not they are parts of one small block. Fragments with distinctive colors, accessory minerals or, in some instances, planar and axial structures almost always can be readily matched, both generally and, by careful use of vectorial data, with regard to their specific orientation² in relation to each other.

¹ Throughout this paper the term foliation applies to the most strongly developed planar structure visible in the marble, regardless of whether or not it represents sedimentary bedding.

² It should be noted that *orientation* refers to the attitude of a structure with respect to geographical or other directional coordinates; it should not be confused with *position* which defines a location.

It is the purpose of this paper to outline an extension of the method of descriptive analysis suggested by Herz and Pritchett to include the study of features of the microfabric of marble, such as the preferred orientation of the [0001]-axes of grains of calcite, which will either confirm a common origin of fragments already suggested by other features, or, what is more important, will enable fragments which show no recognizably distinct features to be compared and contrasted on a basis other than that of general appearance. It is with the techniques now to be described that the simplicity of the method vanishes. The principles and techniques involved cannot be applied except by an experienced worker with a knowledge of structural petrology. The interpretation of statistical diagrams for the preferred orientation of calcite requires specialized knowledge and considerable experience. It must be stated, therefore, that the time-consuming techniques now to be described should be applied only when simpler methods have proved unsatisfactory.

There are three main problems concerning the mutual relationship of fragments of carved or inscribed marble:

1. Are the fragments part of a block of marble quarried in one piece?
2. If so, what was the orientation of each fragment?
3. Is it possible to assign to a marble a definite locality of origin?

It is the purpose of this preliminary paper to discuss whether fabric analysis of marble will assist in solving these problems.

DISCUSSION OF PRINCIPLES INVOLVED

Petrofabric analysis of marble generally shows that the grains of calcite have a greater or lesser degree of preferred orientation of their [0001]-axes (*c*-crystallographic axes). An examination of the existing published diagrams for [0001]-axes shows that two main patterns of preferred orientation commonly occur and these grade one into the other:

1. An area or areas of high concentration at a high angle to the foliation (where present); for example, in Yule marble (Turner, 1949), and the Sonora marble (Turner, 1953);

2. An area or areas of high concentration at a high angle to the foliation spreading into a more or less distinct girdle the pole of which may be parallel to a visible lineation in the fabric; for example, in marbles from Tomintoul and Dulnain Bridge (McIntyre and Turner, 1953), and in marble from the Mojave Desert (Weiss, 1954).

The kinematic significance of these patterns in terms of rock flowage and mechanisms of gliding, twinning, and rotation of grains does not concern us here; only the general form of the common patterns of preferred orientation should be noted. That is, in marbles which are *S*-tectonites with foliation and no lineation (planar control of fabric) there is a tendency for [0001]-axes to lie at a high angle to the plane of foliation; whereas in marbles which are undoubted *B*-tectonites with marked lineation which may be paralleled by small-scale folds (axial control of fabric), [0001]-axes tend to lie in a girdle with one or more maxima normal to the lineation (*B*-axis).

Marble used for making stelai and for building may show either a planar or axial control of fabric to a high degree. Those used for sculpture tend to

have weak linear and planar structures as these are directions and planes of weakness in the fabric. The most sought-after marbles for this purpose will be the "freestone" varieties; that is, marbles which break with approximately equal ease in all directions. In such marbles preferred orientation of $[0001]$ -axes will be correspondingly weak; however, as will be shown below by analysis of a fragment of Parian marble, statistical analysis shows that in even the most equigranular and megascopically isotropic marbles a distinct preferred orientation of the calcite lattice may be found.

The purpose of studying the preferred orientation of calcite in the present context is to decide whether or not the patterns obtained will define a direction or plane in the fabric which will be constant in orientation throughout a block of marble of a size suitable for a stele or a piece of sculpture. There are two features of the patterns of preferred orientation of $[0001]$ -axes which may be important in this respect, namely, the area of maximum concentration and the girdle.

It has already been stated that the $[0001]$ -maximum tends to be oriented at a high angle to the foliation. This angle can vary within one body of marble (Weiss, 1954, p. 36-37). How much it varies within a small block of marble the size of one stele will depend upon the tectonic style of the particular rock. For instance, if the foliation is regular and unfolded, then it is possible that the maximum of $[0001]$ -axes will be inclined to the foliation at a constant angle (fig. 1-a). If, however, on the scale of the block under consideration, the foliation is folded, then, depending upon the type of fold, two simplified possibilities may be suggested (Sander, 1951):

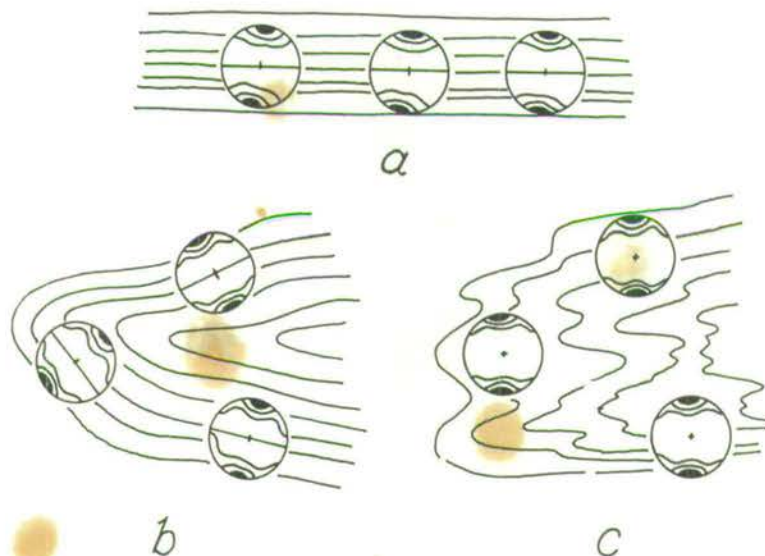


Fig. 1. Some possible relationships in orientation between $[0001]$ -axis maxima and foliation in different marbles.

1. If the fold is capable of being "unrolled," that is, produced by rotation (flexure) of a fabric such as that illustrated by figure 1-a, then the [0001]-axis maximum will have a different orientation with reference to the coordinates of the block in different parts of the fold (fig. 1-b). Ideally, the angle between the maximum and the foliation should be constant.

2. If the fold is incapable of being "unrolled" (probably the common type of fold in marble which has suffered plastic flow), there may be an approach to direction-homogeneity of orientation of [0001]-axes (fig. 1-c).

From these considerations, it is concluded that a single maximum of [0001]-axes in an orientation diagram will not, by itself, define a direction which is likely to be constant throughout one worked block of marble. If a marble has direction-homogeneity of preferred orientation of [0001]-axes, then orienting a single maximum may be used to match fragments with a unique orientation determined by the presence of one inscribed surface, as of a stele. However, if matching of fragments is to be extended to initially large volumes of marble, such as single blocks from which a piece of statuary has been made, then a single [0001]-axis maximum will be insufficient to define a unique orientation for broken fragments even if the preferred orientation is uniform throughout the block. The maximum can define only one constant direction and not the sense of this direction.

The second feature of the patterns of preferred orientation of [0001]-axes is of more importance in the present context. Petrofabric analysis of marbles and other rocks has shown that *B*-axes, defined by the normals to planes of symmetry in the fabric, tend to assume, in strongly deformed rocks, regular orientations over large areas. It is reasonable to suppose that a *B*-axis, even if it is defined only by the girdle pattern of [0001]-axes, generally will be constant in orientation throughout a quarried block of a suitable size to be worked, and probably throughout one large quarry. The *B*-axis will, like the direction defined by a homogeneous preferred orientation [0001]-axis in a maximum, admit a twofold ambiguity in sense (fig. 2).

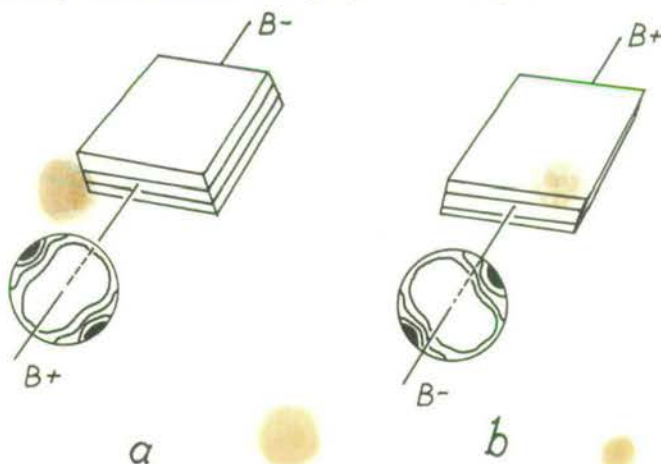


Fig. 2. Orientation diagrams viewed along opposite senses in the direction of the *B*-axis.

The maximum or maxima of $[0001]$ -axes generally to be found around the periphery of girdles are subject to the same variation in orientation with respect to foliation and geographical coordinates as are the single maxima to be found in the orientation patterns prepared from fabrics with planar control.

It is to be concluded from these considerations that the preferred orientation of calcite considered alone will provide, in many instances, insufficient information to establish the relative orientation of fragments of marble where no other guide to orientation is present. It is necessary to seek other means of obtaining constant directions in the fabric of a block of marble. Such a means exists in the technique of dynamically interpreting $\{01\bar{1}2\}$ twin lamellae in marbles with postkinematic crystallization first described by Turner (1953), and subsequently applied by McIntyre and Turner (1953), Weiss (1954), Gilmour and Carman (1954), and Clark (1954). The underlying principle is briefly as follows: if the $\{01\bar{1}2\}$ twin lamellae in a marble have been produced by stress, then it is possible to construct for each grain two mutually perpendicular directions of applied stress (a compression and a tension) which would most readily account for the observed twins. If these directions are plotted for many twinned grains within one thin section and are found to lie in distinctly defined areas of the projection, then it is possible to say that either a compression or tension or both applied in the directions defined by the corresponding maximum concentrations of points could have produced the twinning visible in the marble.

In all marbles with extensive postkinematic crystallization in which the twinning has been studied in this way, either the points of compression or tension or both have been found to lie in distinct and usually strong maxima. This preferred orientation suggests that in marbles with postkinematic crystallization the twinning has been produced at a late stage in the history of the rock, generally after the preferred orientation of $[0001]$ -axes has been acquired. A marble is defined here as showing postkinematic crystallization if the grains of calcite are clear and unstrained with no intense twinning on closely spaced $\{01\bar{1}2\}$ planes, no bending of lamellae or undulose extinction, and no rotated relict twin lamellae indicating complete or nearly complete twinning of grains (Borg and Turner, 1953). Marbles with crystallization defined as pre- or parakinematic show some or all of these features as well as evidence of grain rotation during penetrative movement (Weiss, 1954). Points of compression and tension constructed for twinned grains in these marbles do not lie in simple distinct maxima but fall in coincident *ac*-girdles around the *B*-axis of rotation. These patterns are a result of an apparent rotation of stress axes around *B* caused by relative rotation of individual grains as they become twinned and retwinned during penetrative movement. This rotation destroys interlocking boundaries between grains and, in some marbles, produces granulation.

It is thus possible to distinguish marbles with dominantly postkinematic crystallization from these with dominantly prekinematic crystallization by

microscopic observation. This is important, for only marbles in which a weak stress at a late stage has affected a completely recrystallized fabric will have twin lamellae suitable for the construction of points of compression and tension. If this stress becomes too pronounced it will cause twinning upon $\{01\bar{1}2\}$ -planes with low coefficients of resolved shearing stress, complete or nearly complete twinning upon $\{01\bar{1}2\}$ -planes with high coefficients of resolved shearing stress, and, when the movements become truly penetrative, relative rotation of grains. All of these processes will tend to weaken and disperse the initially strong maxima of compression and tension points which it is possible to construct for very weakly developed twin lamellae in the marbles with a crystallization defined as postkinematic.

Several marbles which appear to have suffered postkinematic crystallization have already been analyzed, and it is known that in specific areas the orientation of constructed points of compression and tension may be constant throughout one hand specimen, in two hand specimens collected one foot apart (McIntyre and Turner, 1953, p. 234, figs. 5a and b), and even throughout one quarry (Gilmour and Carman, 1954, p. 58). It is likely that examination of the twin lamellae in fragments of one worked block of marble with postkinematic crystallization may make possible the recognition of one or two directions (preferred orientation of axes of compression and tension) which have a constant orientation within the block. The seven specimens of marble from Greece, the fabrics of which are described below, all show postkinematic crystallization, and, indeed, it is to be expected that most marbles chosen for their beauty will be of this kind. Marbles with prekinematic crystallization have uneven grain size and a correspondingly dingy appearance when polished.

The directions defined by the maxima of points of compression and tension thus may be constant throughout a varying but generally considerable volume of marble (so far as is known, as large as the volume of one quarry). In addition, it sometimes proves to be the case that these directions are independent in orientation of structures such as foliation, lineation and preferred orientation of $[0001]$ -axes, features which are intimately related to a major penetrative deformation. The orientation of points of compression and tension can never be entirely independent of the orientation of $[0001]$ -axes; for instance, if a compression is applied parallel to an $[0001]$ -axis maximum, then no grains are in a position to twin an $\{01\bar{1}2\}$ -plane. The position of a statistical maximum of points of compression or tension may thus be modified slightly by the preferred orientation of $[0001]$ -axes, especially if it is strong. However, any departures in the constructed points of compression and tension from the actual points so caused will be present to a similar degree in all diagrams prepared from one homogeneous block. Another control of the orientation of the compression and tension points which should be appreciated is the purely geometrical one of a strong preferred orientation of $[0001]$ -axes in a girdle, if the twinning is not produced by stress. The assumption that twin-

ning on $\{01\bar{1}2\}$ is induced by applied stress is made because of the statistical maxima which appear in diagrams constructed by measuring numerous grains in one thin section. However, suppose that the twinning is not mechanically induced and that the twinned lamellae are of random development. If a strong preferred orientation of $[0001]$ -axes into a girdle with a pronounced maximum is present, then this will be accompanied in many instances (McIntyre and Turner, 1953, p. 233, fig. 4a and b) by a similar and coincident preferred orientation of the poles of $\{01\bar{1}2\}$ -planes. This follows from the crystallography of calcite; but there appears in such cases to be an additional preferred orientation of $\{01\bar{1}2\}$ -planes so that two out of the three in each grain lie with their poles in the plane of the $[0001]$ -axis girdle. This orientation is demonstrated by the strong preferred orientation of the edges $[e_1:e_2]$ between strongly marked $\{01\bar{1}2\}$ -lamellae (*e*-lamellae) in each grain into a single sharp maximum at *B* (McIntyre and Turner 1953, p. 235, fig. 5c and d). Thus, if there is fortuitous twinning of $\{01\bar{1}2\}$ planes at a late stage in the history of the marble, then the chances are two to one that the twin lamellae will lie with their poles in or near the plane of the $[0001]$ -axis girdle. In addition, since there is a strong maximum of $[0001]$ -axes in the girdle, and since the point of maximum tension (19° from $[0001]$ by construction), $[0001]$, the poles of $\{01\bar{1}2\}$, and the point of maximum compression (71° from $[0001]$ by construction) lie in the same plane, the pattern of points of compression and tension, which must follow geometrically, is a maximum of points of tension coincident with but weaker than the $[0001]$ -maximum, and a girdle of points of compression in the *ac*-plane with maximum concentrations 71° from the $[0001]$ -maximum. This pattern could easily be misinterpreted as indicating a tension at the $[0001]$ -axis maximum with a compression approximately 90° away in the *ac*-plane. Thus, patterns in which a maximum of points of tension coinciding exactly with the $[0001]$ -maximum, and a maximum of points of compression in the *ac*-plane and approximately normal to the tension maximum, occur together should be doubted as a guide to the orientation of a possible system of stresses. Such patterns may be a faithful guide, but they may equally well be a geometrical consequence of preferred orientation of $[0001]$ -axes. In a rock with a random orientation of grains, the constructed points of compression and tension would likewise be random if the $\{01\bar{1}2\}$ twin lamellae were not deformation structures.

It follows from the above considerations that strong maxima for points of compression and tension in grains of calcite with a weak preferred orientation must be significant. Even in marbles with a strong preferred orientation of $[0001]$ -axes, if the constructed maximum for tension does not coincide with the $[0001]$ -maximum, or if either or both the compression and tension maxima lie outside the *ac*-plane as defined by the $[0001]$ -girdle, then the pattern of orientation of stresses so deduced must be significant. In most of the marbles from Greece analyzed below there is little doubt that the inferred axes of compression and tension are significant. In some specimens both maxima lie outside the $[0001]$ -girdle; in others only one does so. Only

in specimens 1 and 6 do the tension maxima lie near the $[0001]$ -maxima, and even so, the tension girdles spread not in the ac -plane but in a plane normal to the compression maxima.

The significance of the technique of plotting statistical applied stresses has been discussed in some detail because of the importance which will be attached to it in the following synthesis.

From the fabric of an equigranular marble with postkinematic crystallization we can expect to obtain two, three, or, very rarely, four directions, the mutual inclination and orientation of which will be constant for volumes of marble of limited size. These directions are defined by:

1. The maxima of $[0001]$ -axes.
2. The axis of the girdle of $[0001]$ -axes.
3. and 4. The maxima of points of compression and tension constructed from $\{01\bar{1}2\}$ twin lamellae.

Only 2, 3 and 4 are likely to be an infallible guide to the orientation of a fragment, and even two of these may coincide. But in many marbles the three directions will be mutually inclined and will define a unique orientation of the fabric. When this state of affairs prevails, we can expect to be able to solve the first two and possibly, eventually, the third of the problems listed at the end of the first section.

ANALYSIS OF SEVEN SPECIMENS OF GREEK MARBLE

In order to decide how far the dominantly theoretical principles discussed in the last section apply to the more common Greek marbles, seven specimens collected from important quarries in Greece by N. Herz of the U. S. Geological Survey have been examined. The specimens are unfortunately unoriented, and no conclusions of regional importance can be drawn.

Table 1 records the data supplied by Herz concerning these specimens which now form part of the rock collection of the Department of Geological Sciences at the University of California at Berkeley. The numbering in the second column is based upon the British Military Mediterranean grid system; the first two numbers represent the east coordinate and the last two the north coordinate. The first two specimens are presumably the "Hymettian" marble and specimens three to six the "Pentelic" marble of the epigraphers. The seventh specimen is of Parian statuary marble from the island of Paros.

From each specimen two mutually perpendicular oriented thin sections were cut; ideally three should be cut, especially from a marble which is nearly isotropic. In each section 150 $[0001]$ -axes were measured and points of compression and tension were plotted for between 20 and 25 grains markedly twinned on $\{01\bar{1}2\}$ lamellae. Thus for each specimen three diagrams were obtained, one for $[0001]$ -axes, one for points of compression, and one for points of tension in twinned grains. These diagrams are reproduced in figures 3 to 23. Table 2 summarizes the more obvious features of each specimen visible in hand specimen.

TABLE 1

	University of California Number	Herz Number	Coordinates on B.M.M.G.S.	Remarks by Herz
(1)	153-M-1	4241-1	42.5 x 41.2	From Mount Hymettus, just east of Athens, from an old Roman quarry apparently worked in modern times.
(2)	153-M-2	4241-Z	42.2 x 41.2	Same as (1)
(3)	153-M-3	5054-1c	50.7 x 54.3	From Mount Pentelicon, just north of Athens from the Spilia Daveli quarry. This was the largest of the ancient Greek quarries.
(4)	153-M-4	5054-2	—	Quarry just east of (3)
(5)	153-M-5	5056-2	50.85 x 56.5	From Dionysus quarries on north slope of Mount Pentelicon. Quarries date from last half of 19th century.
(6)	153-M-6	5153-1	51.25 x 53.4	From small ancient (?) quarries on southeast slope of Mount Pentelicon above Platanakia. These quarries are in narrow bands of marble dipping steeply in schist.
(7)	153-M-7	6238-1E	62.1 x 38.8	From ancient Lychnites marble mine, Aghias Minor, Paros. These mines produced the famous Parian statuary marbles.

TABLE 2

	Specimen	Color	Foliation, bedding or lineation
(1)	153-M-1	Faintly streaked with white and pale gray	The gray streaks in the rock are axial rather than planar. They constitute a faint lineation almost invisible upon any but a cut and polished surface.
(2)	153-M-2	Clean and white with very faint yellow streaks	No determinable structures can be seen in the rock except the faint yellow streaks which may define a crude foliation.
(3)	153-M-3	Clean white marble with some flakes of mica glistening on broken surfaces	A fairly pronounced linear structure is defined by the orientation of flakes of mica. No foliation is visible.
(4)	153-M-4	Red and green banded marble. Layers alternately rich in piemontite and epidote form the colored bands.	The layers of piemontite and epidote define a pronounced foliation which is folded (the fold axis is <i>B</i>).
(5)	153-M-5	Clean white marble	The rock is almost isotropic with no visible lineation or foliation.
(6)	153-M-6	Grayish white marble with very faint streaks	The streaks may define a crude banding but they are very weak and the pattern is uncertain.
(7)	153-M-7	Pure white marble	Appears to be completely isotropic with no foliation or lineation.

It can be seen from this table that the seven specimens include types which show no obvious macroscopic structures, others may show a weak foliation or lineation or both. All the marbles except 153-M-4 are very pure and the structures, especially foliation, are correspondingly ill defined. Their orientation would be determined in worked material, if at all, only with great difficulty. For this reason their orientation has not been shown upon the orientation diagrams.

From the data contained in figures 3 to 23 it is possible to construct "fabric pictures," one for each specimen, containing the salient features of the orientation diagrams. The data which can be recorded are as follows:

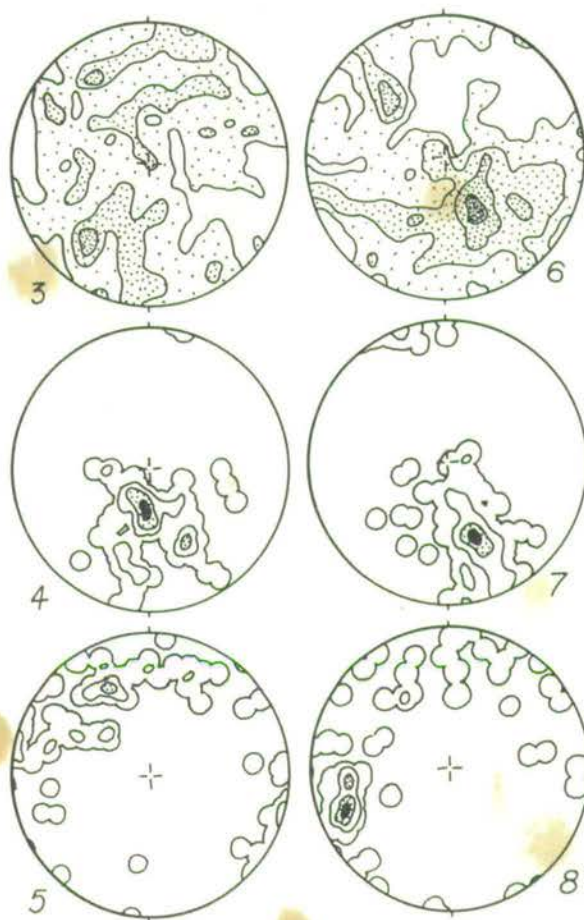


Fig. 3. 300 [0001]-axes in specimen 153-M-1. Contours: 1-2-3% per 1% area. Fig. 4. 50 axes of compression for twin lamellae in specimen 153-M-1. Contours: 2-6-10-14% per 1% area. Fig. 5. 50 axes of tension for twin lamellae in specimen 153-M-1. Contours: 2-6-10% per 1% area. Fig. 6. 300 [0001]-axes in specimen 153-M-2. Contours: 1-2-3-4% per 1% area. Fig. 7. 50 axes of compression for twin lamellae in specimen 153-M-2. Contours: 2-6-10-14% per 1% area. Fig. 8. 50 axes of tension for twin lamellae in specimen 153-M-2. Contours: 2-6-10-14% per 1% area.

1. The maximum M or maxima M_1 , M_2 , and so on, from the orientation diagrams for $[0001]$ -axes. If one maximum is appreciably higher than all others, then only this should be recorded; if, however, there are several maxima of equal strength, then all should be recorded. Each maximum is recorded as the center of gravity of the area enclosed by the highest contour.

2. The great circle M_G defining the greatest spread of the $[0001]$ -axes from the maximum M . If there are several maxima, then M_G should as nearly as possible pass through all of them. It is at best a compromise.

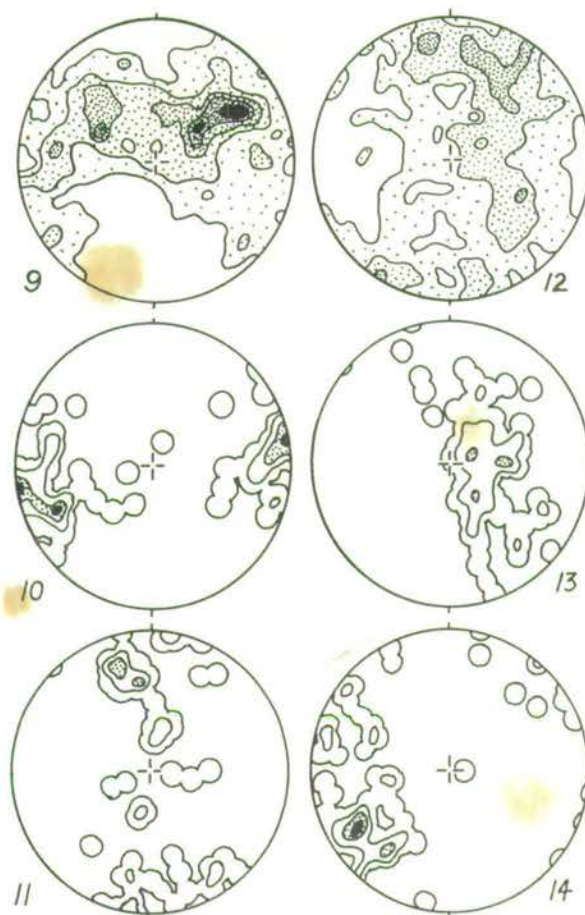


Fig. 9. $[0001]$ -axes in specimen 153-M-3. Contours: 1-2-3-4-5% per 1% area. Fig. 10. 50 axes of compression for twin lamellae in specimen 153-M-3. Contours: 2-6-10-14% per 1% area. Fig. 11. 50 axes of tension for twin lamellae in specimen 153-M-3. Contours: 2-6-10% per 1% area. Fig. 12. 300 $[0001]$ -axes in specimen 153-M-4. Contours: 1-2-3% per 1% area. Fig. 13. 50 axes of compression for twin lamellae in specimen 153-M-4. Contours: 2-6-10% per 1% area. Fig. 14. 50 axes of tension for twin lamellae in specimen 153-M-4. Contours: 2-6-10-14% per 1% area.

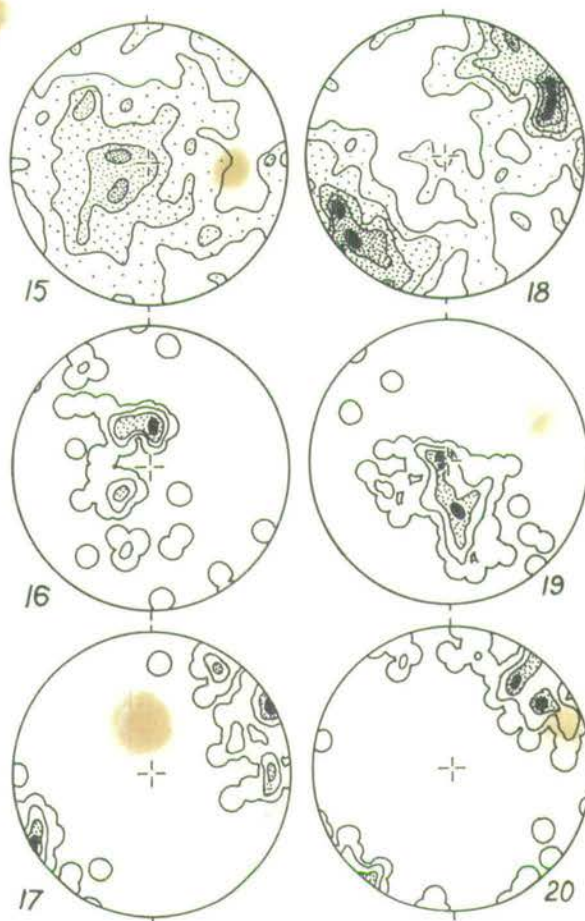


Fig. 15. 300 [0001]-axes in specimen 153-M-5. Contours: 1-2-3-4% per 1% area. Fig. 16. 40 axes of compression for twin lamellae in specimen 153-M-5. Contours: 3-6-9-12% per 1% area. Fig. 17. 40 axes of tension for twin lamellae in specimen 153-M-5. Contours: 3-6-9-12% per 1% area. Fig. 18. 300 [0001]-axes in specimen 153-M-6. Contours: 1-2-3-4-5% per 1% area. Fig. 19. 50 axes of compression for twin lamellae in specimen 153-M-6. Contours: 2-6-10-14% per 1% area. Fig. 20. 50 axes of tension for twin lamellae in specimen 153-M-6. Contours: 2-6-10-14% per 1% area.

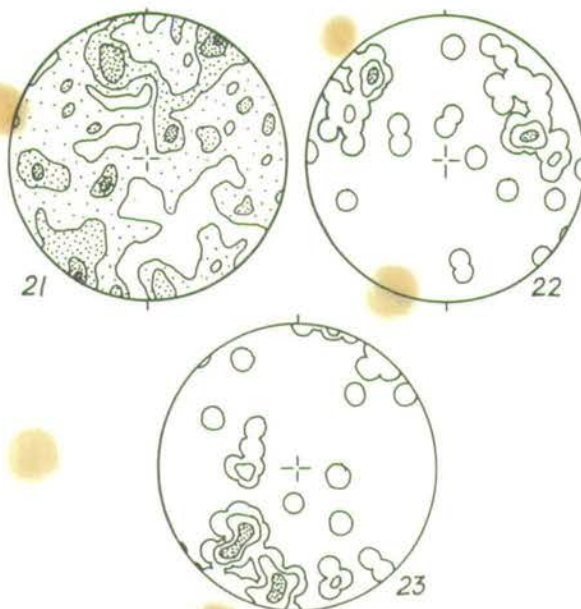


Fig. 21. 300 [0001]-axes in specimen 153-M-7. Contours: 1-2-3% per 1% area. Fig. 22. 40 axes of compression for twin lamellae in specimen 153-M-7. Contours: 3-6-9% per 1% area. Fig. 23. 40 axes of tension for twin lamellae in specimen 153-M-7. Contours: 3-6-9% per 1% area.

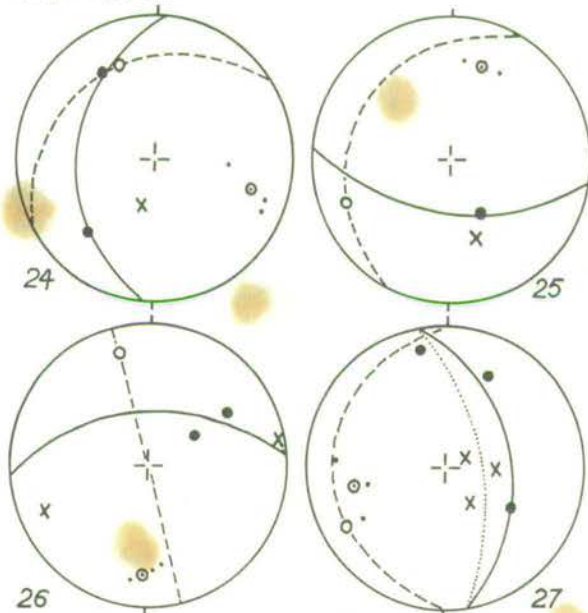


Fig. 24. Fabric picture for specimen 153-M-1. Fig. 25. Fabric picture for specimen 153-M-2. Fig. 26. Fabric picture for specimen 153-M-3. Fig. 27. Fabric picture for specimen 153-M-4. (In each diagram, small dots are A , L and pole of M_G ; circle with dot is compromise B -axis; large dots are M , M_1 , M_2 ; full line is trace of M_G ; cross is C ; dotted line is trace of C_G ; open circle is T ; broken line T_G .)

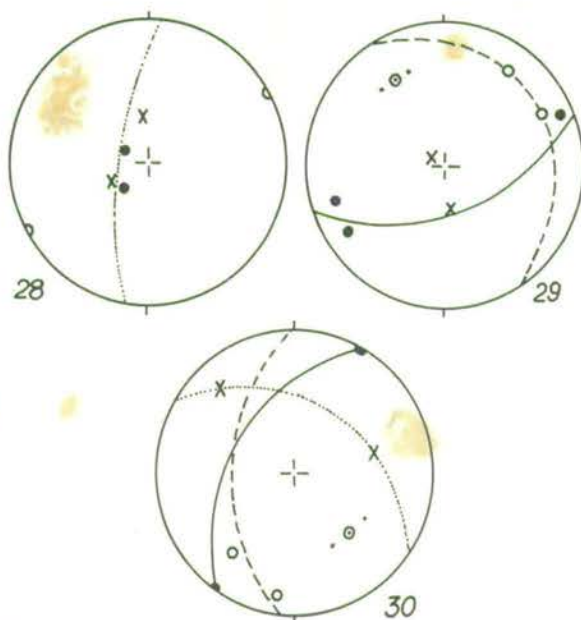


Fig. 28. Fabric picture for specimen 153-M-5. Fig. 29. Fabric picture for specimen 153-M-6. Fig. 30. Fabric picture for specimen 153-M-7. (In each diagram, small dots are A , L and pole of M_G ; circle with dot is compromise B -axis; large dots are M , M_1 , M_2 ; full line is trace of M_G ; cross is C ; dotted line is trace of C_G ; open circle is T ; broken line is trace of T_G .)

3. The center of gravity L of the largest area of zero concentration of $[0001]$ -axes. For an orientation diagram showing a strong girdle concentration of $[0001]$ -axes, L will be the pole of M_G ; but where the girdle of $[0001]$ -axes is wide and diffuse, L may diverge a greater or lesser degree from the pole of M_G . For a fabric which is weakly B -tectonic the true B -axis (B) will be a compromise between L and the pole of M_G .

4. The maximum C or maxima C_1 , C_2 , and so on, for points of compression deduced from $\{01\bar{1}2\}$ twin lamellae. These also are plotted as centers of gravity.

5. In some instances the points of compression spread into a distinct girdle from C , C_1 , and C_2 . The trace of this girdle C_G should be recorded.

6. The maximum T or maxima T_1 , T_2 , and so on for points of tension, deduced from $\{01\bar{1}2\}$ twin lamellae.

7. The girdle T_G spreading from the maximum or maxima of points of tension.

8. The trace of a visible foliation or bedding plane S , where present, should be recorded; also any lineation or fold axis A which can be seen in the specimen. The center of the triangle of error L , A , pole of M_G should be taken as the B -axis in a marble which is a B -tectonite. Planar structures in the seven marbles are so weak that they have been omitted from the fabric pictures.

Most of the directions and planes defined above will help to fix the orientation of the specimen for which they are plotted. As has already been stated, not all of these data are reliable indices of orientation. The $[0001]$ -maxima and the foliation and bedding planes can be used to determine the B -axis (the maxima lie on the ac -girdle and the foliation or bedding planes are tautozonal about B), after which they may be, for simplicity, removed from the fabric picture. The fabric pictures for the seven specimens are reproduced in figures 24 to 30. Each picture has the same orientation as the corresponding orientation diagrams in figures 3 to 23.

METHOD OF INTERPRETING FABRIC PICTURES AND ITS LIMITATIONS

General procedure.—The fabric pictures can be used in two ways to compare fragments of marble:

1. The salient features of the pictures should be directly compared. If they are similar in all of the important respects mentioned above, then it is likely that the fragments are part of one small body of marble. Obviously, unavoidable inaccuracies in the method of preparation of the orientation diagrams mean that the resemblance will be inexact; but complete dissimilarity of the fabric pictures will mean that the fragments from which they were prepared cannot have formed part of one small block.

2. Once it has been established that several fragments have similarity of fabric pictures strong enough to indicate a common origin, the triclinic symmetry which, in most examples, will be a feature of the fabric pictures, will define for the fragments a unique orientation. In order most easily to compare the pictures, those which show good axial control of fabric should be rotated until viewed along B . There are two senses to the direction B ; but, if the pictures are plotted upon tracing paper, then they may be viewed also from back to front for purposes of comparing the opposite senses, provided that they are also rotated through 180° about B with relation to the specimen (fig. 31).

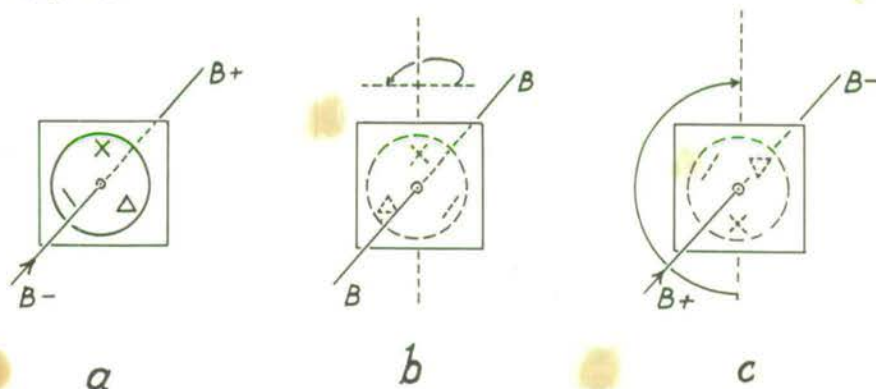


Fig. 31. Procedure in rotating tracing of orientation diagram in plane normal to B to view in opposite sense of B .

a. Orientation of tracing in relation to the two senses of B . Arrow shows the sense of viewing ($B+$).

b. First step; rotation of tracing around vertical axis.

c. Second step; rotation of tracing around B . The orientation diagram seen through the tracing paper is now viewed in the sense shown by the arrow ($B-$).

If the pictures show planar control of fabric, that is, [0001]-axis maxima without girdles, then they should be rotated until viewed along the direction defined either by the tension or the compression maxima (the more clearly defined direction is selected). There are two senses and the pictures can be viewed along either as shown in figure 31.

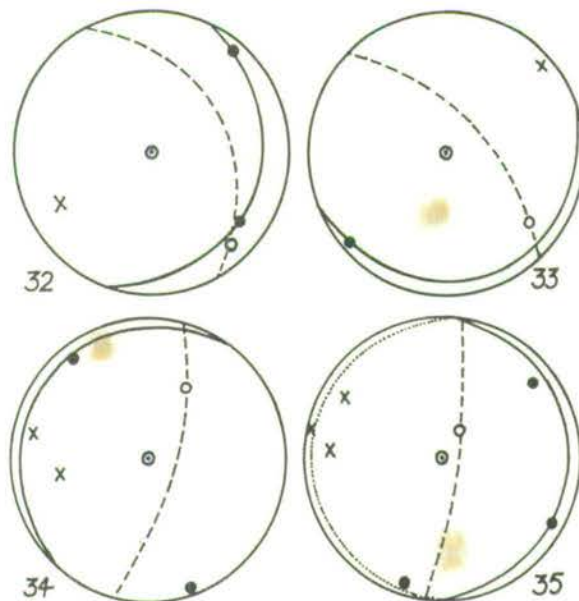


Fig. 32. Fabric picture for specimen 153-M-1 rotated until viewed along *B*. Fig. 33. Fabric picture for specimen 153-M-2 rotated until viewed along *B*. Fig. 34. Fabric picture for specimen 153-M-3 rotated until viewed along *B*. Fig. 35. Fabric picture for specimen 153-M-4 rotated until viewed along *B*.

The fabric pictures reproduced in figures 24 to 30 have been prepared from unoriented specimens. However, specimens 1 and 2 are from the same quarry on Mount Hymettus and the corresponding fabric pictures, when rotated until viewed down the compromise *B*-axis (figs. 32 and 33), show similarity. Unfortunately, this cannot be checked against a known orientation. Similarly, the fabric pictures for specimens 3 and 4, collected from adjacent quarries on Mount Pentelicon, have a mutual resemblance when rotated (figs. 34 and 35). Fabric pictures from the remaining specimens are reproduced in order to show that from a variety of Greek marbles distinct fabric pictures are obtained by analysis. The most weakly defined picture is that prepared from the Parian statuary marble (specimen 7); but even in this picture the maxima of compression and tension are distinct and the *B*-axis is defined by the preferred orientation of [0001]-axes (figs. 21 to 23 and fig. 30).

General procedure in examining a set of fragments believed to be part of one worked block should be as follows:

Procedure with fragments believed to be part of one stele.—This is the simplest case as the single inscribed surface presumably present upon each

fragment uniquely orients the fragments in relation to each other. Figure 36 shows a hypothetical restoration of a stele based upon the orientation defined by the inscribed surface. Certain fragments fit together along broken surfaces; for example, fragments 6, 8 and 9; 1 and 2; 3 and 4. This confirms immediately that each group formed part of a single block, but does not confirm that the three groups are similarly related. The circles inscribed upon the fragments contain hypothetical idealized fabric pictures prepared from the respective fragments. The similarity in the position of B , T and C in the pictures prepared from fragments 1, 2, 3, 4, 6, 8, and 9 confirm that they were part of the same stele. The homogeneity of the block also is established. The pictures for the remaining unattached fragments prove by their dissimilarity both from the other pictures and amongst themselves that they are not part of the main stele or even of one stele. The variation in position and size of M , M_1 , M_2 shown in the pictures for the selected fragments in figure 36 is to show that such maxima can have considerable range in orientation in one block of marble. It is, however, important that the maxima should lie close to or on the great circle the pole of which is B .

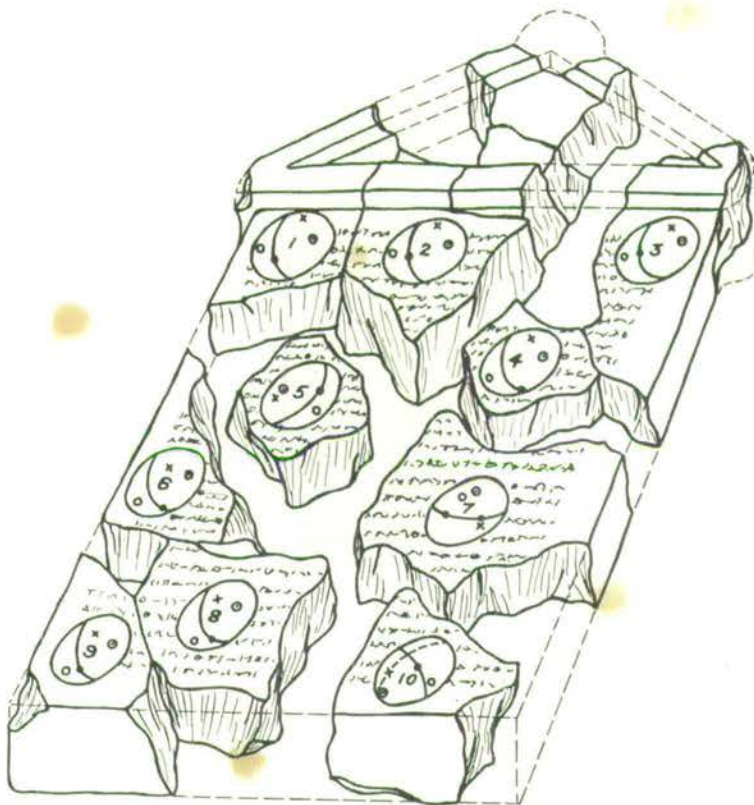


Fig. 36. Hypothetical restoration of a fragmental stele. Fragments 5, 7 and 10 are not part of the stele. (Full circle is trace of M_G ; black dots are M , M_1 , M_2 ; cross is C ; broken line is C_G ; open circle is T ; circle with dot is B)

Procedure with fragments believed to be part of a work in marble other than a stele.—Treatment of such fragments presents much more difficulty and is open to more error than is the treatment of fragments of a stele. For some of the fragments there will be no morphological clue to relative orientation, although many fragments will have their orientations fixed to some extent: for instance, there is only a limited range of orientation of a foot or a head in relation to the trunk of a statue. The first stage in a work of restoration is to prepare fabric pictures from all large important fragments. If there is axial control of fabric the pictures should be rotated until viewed along *B*. The pictures then should be compared, and fragments with pictures which are obviously unlike the majority should be rejected at once. As in the last example, large fragments and groups of fitting fragments may be used to establish the degree of homogeneity of the fabric.

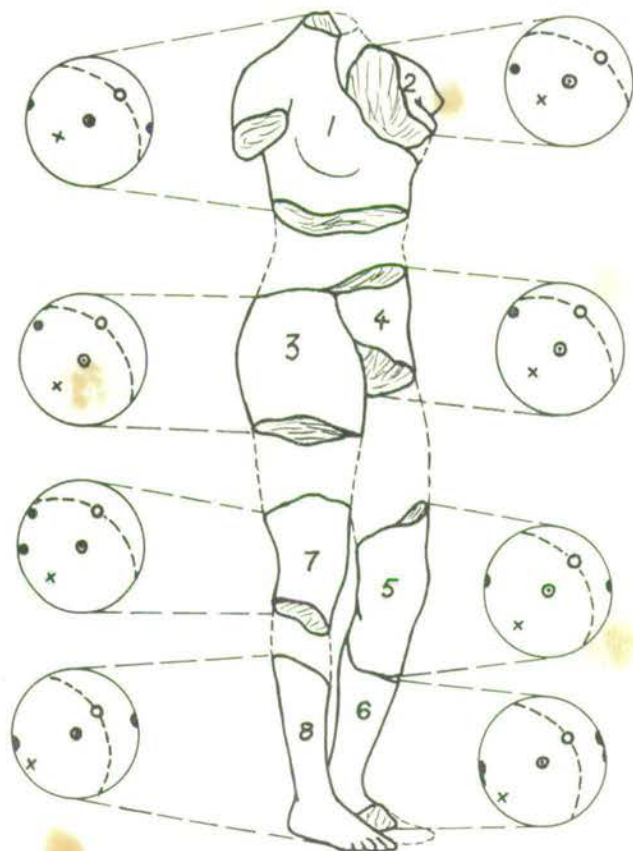


Fig. 37. Tracing of the Aphrodite of Cyrene showing mode of restoration if this statue had been found in fragmental and incomplete condition (only the head and arms are actually missing). The eight fabric pictures prepared from the eight fragments are rotated so that they are viewed along the same sense of the compromise *B*-axis. The relative orientation of the fragments so defined is thus fixed, and the only possible positioning of them is as shown.

It will generally be possible to establish homogeneity in a marble, and, once this has been done, the fragments selected for their mutual similarity of fabric pictures can be oriented with respect to each other. If, as will often be the case, the *B*-axis and the compression and tension maxima define a tri-
 clinic symmetry for the fabric picture, then the relative orientation can be

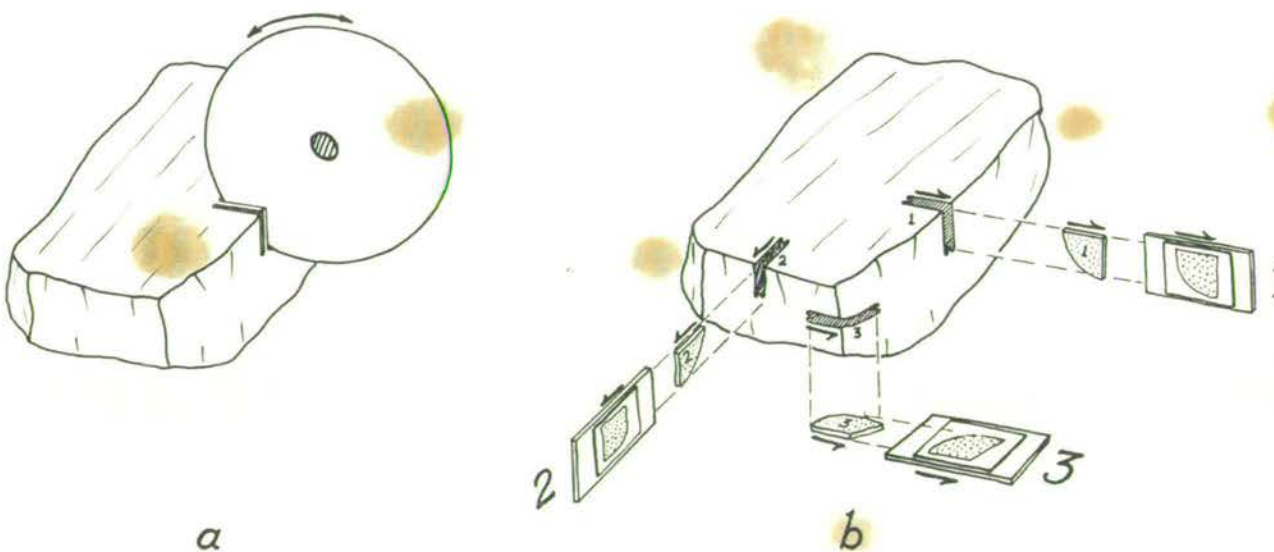


Fig. 38. Procedure in cutting and orienting thin sections.

a. Parallel saw cuts made with rotary saw.

b. Triangular leaves are snapped out and are made into three mutually perpendicular sections with known orientation.

determined with little difficulty. If, however, the symmetry of the picture is monoclinic (it is unlikely that it will be either orthorhombic or axial), then there will be two possible orientations for each fragment. Such ambiguities will in many instances be solved by considering the external form of the fragments. A hypothetical restoration of this type is shown in figure 37.

This technique of restoration is thus largely, as are so many structural techniques involving kinematic or dynamic interpretations, a matter of trial and error. No rule of thumb will ever be developed and each specific problem must be treated in a different manner. In many cases the technique should prove successful, in others it may fail; but in all it will require care, patience, and an ability to evaluate the significance of data such as could be possessed only by an experienced worker.

Procedure in cutting and orientation of thin sections.—Best results will be obtained by cutting *three* mutually perpendicular thin sections and measuring data from each. The resultant diagrams should be rotated into one plane and combined.

The actual cutting of thin sections from valuable fragments should be performed with great care by a skilled technician. Sections are best made from broken edges and surfaces of fragments as shown in figure 38-a. Two parallel saw cuts are made to a suitable depth as close together as the nature of the rock will allow, and a triangular leaf is snapped out, after marking its orientation with respect to the fragment. This leaf is carefully mounted and made into a thin section of which the actual orientation relative to the fragment is accurately known. Such sections are prepared from the three mutually perpendicular planes as shown in figure 38-b. As an additional check upon the orientation of the thin section the fragment, after cutting, should be drawn or photographed and the exact orientation of the finished sections shown. This whole operation should be conducted with utmost care and accuracy as upon it will depend the significance of the analysis.

After the sections have been cut, the narrow slots so left in the specimen are filled with plaster or another suitable filler, and the narrow band is colored most nearly to resemble the rock. If cutting is confined as far as possible to already broken surfaces, then the appearance of the fragment will not be harmed. Fragments with irregular or rounded surfaces may be dealt with in the same way.

Time involved in analysis.—The measurement of the data from the thin sections is a time-consuming procedure. In a medium-grained marble such as those described above, to measure 150 [0001]-axes and 25 twinned {0112}-lamellae in each of three sections and to rotate and contour the diagrams into one plane will take an experienced worker from 15 to 20 hours. In some marbles with fine grain the time required may be longer, whereas in other coarse-grained marbles, with plentiful and marked twinning, it may be shorter. To complete one restoration of, say, 10 fragments would take a minimum of 150 working hours. Most stelai should be dealt with in considerably less time than this, as the fragments will generally be much fewer in number.

SUMMARY OF CONCLUSIONS

The following conclusions are stated as simply as possible for use of geologist and archeologist alike:

1. Detailed fabric analysis of marble indicates that from any one specimen of marble a "fabric picture" may be prepared which in many instances will define a unique orientation in space for the specimen. The orientation is generally fixed by three directions:

(a) The compromise *B*-axis deduced from the [0001]-axis orientation of the grains of calcite and the megascopic lineation, where present.

(b) and (c) The statistical maxima of points of compression and tension deduced from twinning upon {0112}.

2. Previous work indicates that these three directions tend to have approximately constant orientation throughout bodies of marble of various size. It is likely that they will prove always to be constant in orientation throughout a block of a size suitable for inscription or sculpture.

3. Making use of the fabric pictures, it will be possible to restore a stele or other work in marble; firstly, by selecting those fragments which have sufficiently similar fabric pictures to be part of one block; and, secondly, by establishing the relative orientation of each fragment.

4. The seven specimens of Greek marble analyzed have all yielded strong and distinctive fabric pictures. This suggests that the principles outlined above will be applicable to many problems of ancient Greek art.

5. It is necessary to point out that this paper is a preliminary description of a technique which is at the moment still unapplied. It is difficult to find suitable problems outside Greece; and, before the work is carried too far in analyzing specific examples, it would be well to visit the more important quarries in Greece and establish the degree of homogeneity of the marble masses themselves. Incidental to this study, the orientation of large and small scale structures within the marble-bearing formations of Attica should be examined. The separate identity of the Hymettian and Pentelic marbles has been questioned by Kober (1929) and it is possible, as he suggests, that nappe structures exist in Attica. Mapping of axial structures in this region may well prove that much of the crystalline series of Attica is homoaxial, and it may be possible, by axial projection of a geologic map, to prepare a tectonic profile and establish a definite structural relation between the various bodies of marble. Also, axial control of fabric may be limited to certain well-defined bodies of marble, thus limiting marbles which are *B*-tectonites to certain places of origin.

Thus, application of the technique outlined above should be preceded, wherever possible, by a field investigation of the marble-bearing formations from which the worked fragments are thought to have been derived. Obviously, certain specific problems, such as the restoration of one fragmentary stele, could perhaps be solved with no knowledge of the field relations of the source marble; but systematic field investigation of the marbles in one general source area may eventually make possible not only the restoration of fragmentary works of marble but also the tracing of the quarry, or at least the general area from which the marble had been obtained. It should certainly

be possible to assign a marble to a country of origin; for instance, a Roman copy in Italian marble of a Grecian original should be distinguishable readily from a true Grecian work in marble from Greece.

It is possible that the field outlined in this paper can be enlarged considerably, perhaps, with increasing petrofabric knowledge, even to include the restoration of works in rocks other than marble; but much groundwork remains to be done before the techniques suggested can be established soundly and applied widely. There is no reason, however, why certain specific problems should not be tackled with the knowledge already to hand, as the writer intends to do in conjunction with Dr. W. Kendrick Pritchett of the University of California. There must be many archeological problems of the kind suggested which a small amount of work upon a small number of thin sections would solve simply and quickly.

ACKNOWLEDGMENTS

The writer wishes to record his thanks to Dr. F. J. Turner and Dr. W. K. Pritchett of the University of California who suggested the problem and gave guidance and advice. Thanks also are due to Dr. Norman Herz of the U. S. Geological Survey who provided the specimens of marble collected by him in Greece, and to Dr. D. B. McIntyre of the University of Edinburgh for reading the manuscript. The optical measurements were made with equipment purchased by the Moray Endowment.

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I. 3. Contrasted Styles of Folding in the Rocks
of Ord Ban, Mid-Strathspey.

(Jointly with D.B.McIntyre and M.Kürsten)

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Contrasted Styles of Folding in the Rocks of Ord Ban Mid-Strathspey¹

By L. E. WEISS, DONALD B. MCINTYRE, and MARTIN KÜRSTEN

(PLATES I AND II)

ABSTRACT

On Ord Ban, quartzite in superposed recumbent folds trending north-south is separated by a slide from mica-schist, granulite, and marble folded in monoclines trending east-west. The reasons for distinguishing between these two styles of folding are given, and the characters of the two styles are contrasted. A fold in quartzite and a fold in marble are described in detail, and kinematic interpretations are attempted. It is concluded that evidence of an early deformation involving mylonitization has been preserved in the quartzite, and that the latest tectonic event distinguishable was the production of the monoclines with attendant twinning of calcite and dolomite.

I. INTRODUCTION

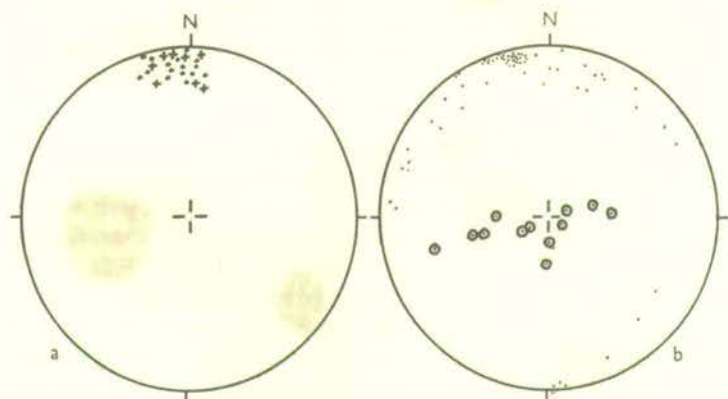
THE trend of the folds in the Scottish Highlands was formerly believed to be dominantly north-east-south-west (e.g. Peach and Horne, 1930, fig. 27), but, as a result of the petrofabric work of Coles Phillips, the general trend in the Northern and Central Highlands appeared to be north-west-south-east (Phillips, 1937, fig. 5). More recently it has been discovered (McIntyre, 1951A) that the overall pattern is in fact complex, but essentially homo-axial regions up to 100 square miles in area have been described (e.g. McIntyre, 1951B). On the small hill of Ord Ban above Loch an Eilean, near Aviemore, the tectonic relationships of the various rocks are exceptionally complex. One of us has already recorded that in the Ord Ban quartzites "The plunge of the fold-axis is remarkably constant, but it does not coincide with that of the schists or of the marbles except where the latter are closely associated with the quartzites" (McIntyre, 1951C, p. 50). This locality was visited in the course of an excursion to the Highlands after the Edinburgh Meeting of the British Association in 1951. One of the participants, Dr. Kvale, was so impressed by the remarkable diversity which he had been shown that he has further emphasized the interest of the Ord Ban exposures (Kvale, 1953, p. 63).

On the north-eastern slopes of Ord Ban, marble and quartzite occur in neighbouring outcrops. The fold-axis in the marble is nearly at right angles to that in the quartzite, and the forms of the folds in the two rocks are very different. A note on the megascopic structural characters of the quartzite has already been published (McIntyre,

¹ Locality map, McIntyre and Turner, 1953, text-fig. 1.

1951c), and a petrofabric analysis of a specimen of the marble has also been recorded (McIntyre and Turner, 1953, pp. 236–240). In view of the unusual interest of this small but complex area, it seemed desirable to investigate the tectonics of the marble and of the quartzite in further detail. A number of features have emerged which are new to Highland geology, and, although much of importance undoubtedly remains to be discovered in the rocks of Ord Ban, we feel that it is now possible to outline the characters of two of the contrasted styles of folding in this area.

The folds selected as typical of the two styles occur in rocks of different composition. In a body of quartzite, overlain by mica-schist and siliceous granulite, superposed recumbent folds occur as

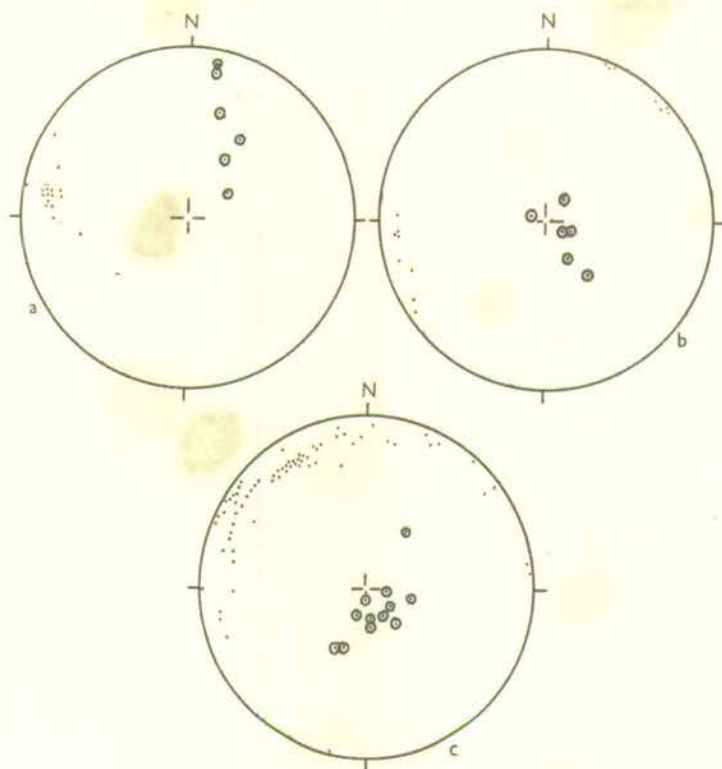


TEXT-FIG. 1.—(a) Lineations (crosses) and fold-axes (dots) measured in the quartzite.
(b) β -diagram for quartzite. Circles with dots are π -poles.

illustrated by McIntyre (1951c, figs. 3 and 4). The axis of these folds (B_1) trends approximately north-south, with shallow plunge to the north. Such folds are found only in the quartzite. In the mica-schists and granulites overlying the quartzite, and separated from it by a zone of movement smeared with a thickness of several inches of mica, small monoclinical folds sporadically occur. In general these folds are about axes (B_2) trending approximately east-west and plunging gently to the west. About 300 yards to the north of the quartzite a very large fold of the same form involves also a thickness of coarsely crystalline marble (see McIntyre and Turner, 1953, p. 236, and text-fig. 6a). This fold also overlies the quartzite which is carried underneath by the plunge of its north-south fold-axis.

A strong lineation in the quartzite parallels the fold-axis of the recumbent folds (Text-fig. 1a). No megascopic lineation is present

parallel to the east-west trending fold-axis in the overlying mica-schist. A β -diagram prepared from the quartzite (Text-fig. 1b) shows a single strong maximum coinciding with the maximum concentration of lineation (B -axes). Text-figs. 2a, b, and c are β -diagrams prepared from the overlying series of mica-schist, granulite, and marble. The first two are from homogeneous areas where monoclinical folds are

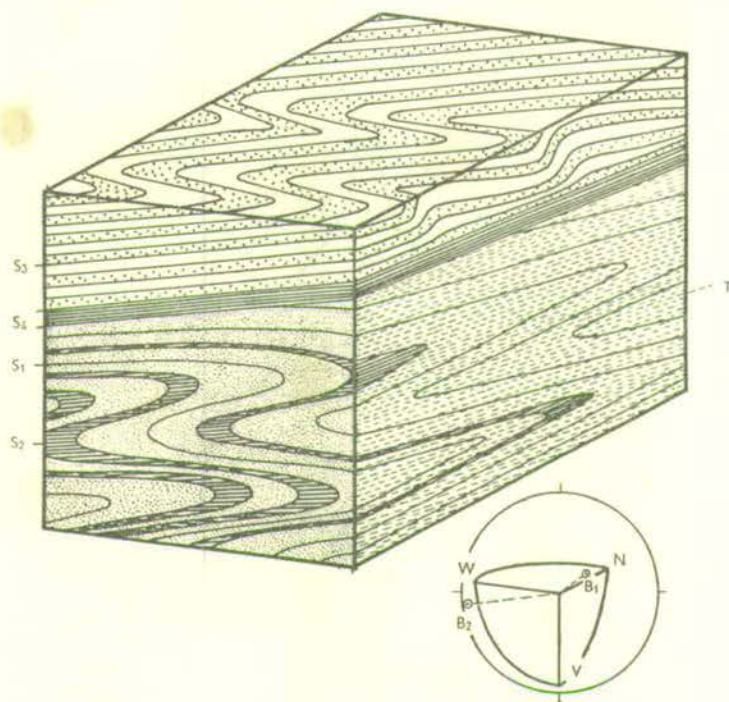


TEXT-FIG. 2.—(a), (b), and (c), β -diagrams for mica-schist, granulite, and marble series. Circles with dots are π -poles.

developed; the third is from an area of irregularly undulating foliation which appears to be inhomogeneous. The ~~north-south~~ ^{east-west} trending axis is clearly defined in Text-figs. 2a and b, whereas Text-fig. 2c suggests a compromise between the two axes.

Folds of the two contrasted styles occur within three feet of one another separated by the zone of movement (Plate 1b). Text-figure 3 is a diagrammatic representation of the structures visible in the rocks on either side of the zone of movement (slide). One fold of each style has been selected for fabric analysis. The fold in the quartzite (axis B_1)

is one of those shown in Plate Ia. The fold in the mica-schist, granulite, and marble series is the large fold described by McIntyre and Turner (1953). It differs from those shown in Plate Ib only in its size and in that it involves marble. The kinematic and dynamic interpretations of phenomena of twinning and preferred orientation in calcite and dolomite, made possible by recent experimental work, make this the obvious choice.



TEXT-FIG. 3.—Relationship of planar and linear structures on either side of the slide separating the quartzite from the mica-schist, granulite and marble series.

S_1 micaceous laminae and layering in quartzite.

S_2 axial-plane foliation of micaceous cores in quartzite.

S_3 foliation of the mica-schist, granulite, and marble series (separated from the quartzite by the slide).

S_4 foliation developed in micaceous layer along zone of movement.

T trace of B_1 -lineation.

W, west; N, north; V, vertical downwards.

Orientations are given on an *orthographic* projection (lower hemisphere) in inset. The use of an orthographic net in constructing this particular block-diagram is discussed elsewhere (McIntyre and Weiss, 1954).

II. FOLD IN QUARTZITE

(a) Megascopic Fabric

Plate Ia shows a profile of a recumbent fold in the quartzite of Ord Ban, one of several superimposed folds described by McIntyre. The fold is defined by layers of quartz grains of slightly differing size interspersed with micaceous layers (S_1). In the core of the fold the micaceous layers are greatly thickened by material squeezed from the limbs, and are impressed with a foliation (S_2) defined by a preferred orientation of flakes of mica parallel to the axial-plane of the fold. This axial-plane foliation does not penetrate into the layers of quartzite. The axis of the fold plunges at 6° to N. 348° , and is paralleled by a marked lineation defined, in the micaceous layers by the intersection of S_1 and S_2 and, in the quartzose layers by a marked alignment and elongation of small grains. The symmetry of the structure is broadly monoclinic on the scale of the fold, with a plane of symmetry normal to the fold-axis. The lineation is in B .

(b) Microscopic Fabric

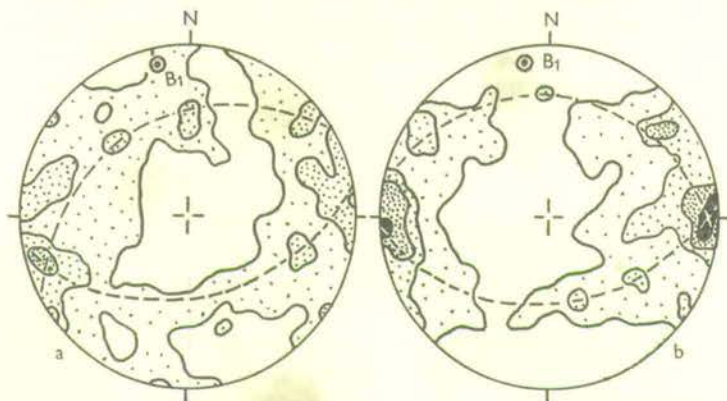
Two specimens of quartzite have been selected for fabric analysis; one (0.8) is from a limb of the fold, the other (0.9) is from the hinge of the fold where S_1 is curved. Plates IIa and b are photomicrographs made with crossed nicols of specimen 0.8 in *ac*- and *ab*-section respectively. The *bc*-section is exactly similar to the *ab*-section. The rock consists of a mosaic of large, minutely interlocking quartz grains. Measurement of three mutually perpendicular dimensions shows that there is no tendency for the grains to be elongate in one direction more than another. The ratios of apparent grain dimensions in thin sections (specimen 0.8) obtained by measuring many grains are $a : B : c = 1.4 : 1.4 : 1.3$. The average mean grain dimension is 2.5–3 mm.

Each of the large quartz grains encloses small rounded grains of feldspar. It can be seen from Plates IIa and b that, whereas in *ab*-section the feldspar grains are elongate and arranged in lines parallel to B (true also of the *bc*-section), in *ac*-section they pepper uniformly the large quartz grains with no apparent regularity. The visible lineation in the quartzite is defined by this arrangement of tiny grains of feldspar which are undoubtedly the rolled and broken fragments of larger grains disrupted during a phase of penetrative movement. The arrangement of the fragments in lines and not in planes shows that the movements¹ during this phase consisted mainly of axial-flow of the rock mass along B_1 .

¹ *Movement* should not be confused with *transport*. Movement may be either parallel or normal to B , whereas, in a fabric with monoclinic symmetry, transport is *always* normal to B . For a discussion of these terms see Weiss, 1954a, pp. 76–7.

The fragments of feldspar constitute a *B*-helicitic structure,¹ preserving in their arrangement a guide to the orientation of the movements during the main phase of deformation which preceded complete post-kinematic recrystallization of the quartz. The large quartz grains are unstrained (apart from slight undulose extinction); there are no deformation lamellae or bands to indicate incipient penetrative movement in the fabric.

(i) *Orientation Data*.—The preferred orientation of quartz has been studied in four thin sections from specimen 0.8 and three from specimen 0.9. The point diagrams obtained by measuring all grains in each section were rotated into geographical horizontal, superimposed and



TEXT-FIG. 4.—(a) 396 [0001]-axes of quartz measured in four sections cut from specimen 0.8. Contours: 1–3–5 per cent per 1 per cent area. (b) 312 [0001]-axes of quartz measured in three sections cut from specimen 0.9. Contours: 1–3–5–7 per cent per 1 per cent area. Broken lines show apparent (*OkI*)-girdles.

contoured to produce Text-figs. 4a and b. The patterns of preferred orientation of [0001]-axes so obtained mutually agree. In each there is a strong maximum normal to B_1 spreading into two complete or nearly complete (*OkI*)-girdles. The preferred orientation is independent of S_1 and appears to be homogeneous. Unbending of the fold would destroy this homogeneity and not establish a pre-existing fabric; this style of fold is called “non-unrollable” by Sander (1951).

The symmetry of the diagrams themselves is approximately ortho-

¹ The term *helicitic structure* is used to describe an arrangement of inclusions which defines folded *s*-surfaces relict within a porphyroblast. Such an arrangement is a general case denoting a pre-existing, externally rotated (folded) *s*-surface. We suggest that this structure be termed *R-helicitic*. The special cases are arrangements of inclusions in planes and lines. In the former the radius of curvature is infinite, in the latter infinitesimal. These arrangements could be termed *S-helicitic* and *B-helicitic* respectively. The structures must, of course, be determined in three dimensions.

rhombic, although the insertion of the trace of S_1 imparts to them a monoclinic symmetry. However, the diagrams do not have the marked monoclinic symmetry of *ac*-girdles with inclined maxima which are so often a feature of quartz-tectonites.

(ii) *Preferred Orientation by Recrystallization*.—Study of the fabric of pure quartz-rocks which have been heavily deformed suggests that penetrative movements without recrystallization generally leads to a complete breakdown of an initially coarse-grained rock by granulation. The present experimental evidence suggests that quartz cannot flow plastically in the manner of calcite (Griggs and Bell, 1938). The end-product of the process of granulation is a fine-grained mosaic of quartz grains surrounding fragments of any accessory minerals present. The style of the movement responsible for the granulation can generally be determined by a study of the arrangement of the accessory minerals. In some examples they are arranged in planes which may be smeared with mica; in others, such as the Ord Ban quartzite, they are arranged in lines.

Granulation of quartzites occurs when the rate of deformation greatly exceeds the rate of crystallization. The process may be followed, as in the Ord Ban quartzite, by intense postkinematic crystallization. The folding and lineation of the Ord Ban quartzite have been produced by penetrative movement prior to recrystallization. No A.V.A.¹ has been made because the rock is too coarse-grained for an analysis of one section to yield significant results. But the partial diagrams prepared from the different sections in each specimen are strikingly similar, indicating an overall direction-homogeneity of orientation. In this and other features it resembles closely a quartzite described elsewhere by one of us (Weiss, 1954A, pp. 69–70, fig. 46, and plate viii). An A.V.A. made of this rock (of finer grain than the Ord Ban quartzite) proved that the orientation of quartz was direction-homogeneous. The pattern of preferred orientation, which was the same as that of the Ord Ban quartzite, was attributed to recrystallization *in situ* under stress without penetrative movement. Similarly, the Ord Ban quartzite shows no evidence of penetrative movement subsequent to or during crystallization.

The pattern of preferred orientation in a quartzite which has been recrystallized from a fine-grained deformed quartz-schist or mylonite to form an unstrained, interlocking mosaic of quartz grains must have been produced by recrystallization in one of two ways:—

- (1) By unselective growth of seed granules formed and oriented during the phase of penetrative movement. The pattern so produced will reflect exactly the preferred orientation of the granules;

¹ *Achsenverteilungsanalysen*. See Ramsauer, 1941, and Weiss, 1954A.

- (2) by selective growth of seed granules with a certain preferred orientation in an anisotropic medium. The anisotropy may be one of either fabric or stress.

A preferred orientation produced in any one of these ways is likely to agree in symmetry with the structures produced during the main phase of movement.

(c) *Kinematic History of the Quartzite forming the Fold*

A quartzite, almost certainly of sedimentary origin, was strongly folded into superposed recumbent folds about shallowly plunging axes. The penetrative movement accompanying the folding reduced the quartz to a fine-grained condition, probably by granulation, and disrupted grains of feldspar which were also present. The folding does not appear to have been either flexural-slip or shear-folding. The main movement in the rock appears to have been elongation along B_1 as is shown by the "streaming" of the fragments of feldspar. There is no evidence that the foliation S_1 was at any stage a plane of marked transport or slip normal to B_1 on the scale of the fold. The style of the folding suggests hindered transport. The mass of quartzite forming the fold has been shortened normal to the axial-plane, slightly lengthened parallel to the axial-plane and normal to B_1 , and greatly lengthened parallel to B_1 . Although all folds possess monoclinic symmetry, the movements which produced this fold could have been ideally orthorhombic (cf. Weiss, 1954A, pp. 40-4). If the fold has been developed from a horizontal planar structure, then there must have been external rotation around B_1 of the mass as a whole. In the micaceous layers, which have been squeezed from the limbs into the core of the fold during shortening of the mass normal to the axial-plane, the mica flakes have come to lie with their {001} cleavages in the plane containing the two direction of elongation, thereby producing the foliation S_2 . The fold is not a shear-fold since S_2 does not penetrate the quartzite layers as a visible slip-plane. The last phase in the history of the rock was recrystallization under static conditions.

III. FOLD IN MARBLE

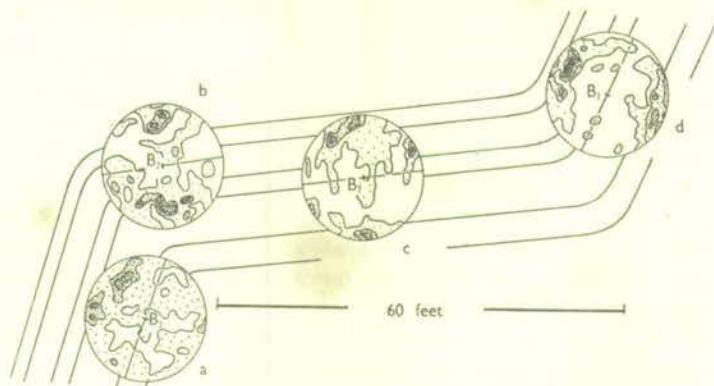
(a) *Megascopic Fabric*

The fold which affects the marble is shown diagrammatically in Text-fig. 5. Compared with the fold previously described, it has a very different style and it is about an axis which plunges 10-12° towards N. 282°. When referred to the horizontal plane, the fold is monoclinical with one vertical and one horizontal limb. The only foliation visible is that forming the fold (S_3) and it appears to be sedimentary

bedding. The marble shows no megascopic lineation (see grain dimensions given by McIntyre and Turner, 1953, p. 236).

(b) *Microscopic Fabric*

McIntyre and Turner (1953, pp. 236-9) have already described phenomena of preferred orientation and twinning in a specimen (0.3) collected from the fold. Three more specimens (1, 2, and 3) were collected from positions on the fold shown in Text-fig. 5. Specimen 1 is a calcite-marble with layers rich in calc-silicates and plagioclase. Flakes of brown mica are oriented with $\{001\}$ parallel to S_3 . Specimen 2 is also a calcite-marble rich in calc-silicates, but no plagioclase or



TEXT-FIG. 5.—Profile of fold in mica-schist, granulite, and marble series. The preferred orientation of $[0001]$ -axes of calcite and dolomite in the four analysed specimens is shown in the superimposed diagrams. Contours: calcite, 1-3-4 per cent per 1 per cent area; dolomite, 1-3-5-7 per cent per 1 per cent area. (a) Specimen 0.3, (b) specimen 1, (c) specimen 2, and (d) specimen 3.

free quartz is present. Specimen 3 is a dolomite rock containing no calcite. Calc-silicates are abundant and S_3 is well marked.

All the specimens appear to have suffered extensive postkinematic crystallization, for there is complete absence of either granulation or internally rotated deformation-structures in the grains. Specimens 1 and 2 both show weak twinning on $\{01\bar{1}2\}$ -lamellae in calcite. In specimen 1, twelve out of 100 grains are weakly twinned; and in specimen 2, twenty-one out of 100 grains. The grains in specimen 3 (dolomite rock) generally have well developed lamellae or partings parallel to $\{02\bar{2}1\}$. The proportion of grains with only one set of lamellae is much higher than in the calcite-marbles. Thirty out of fifty show optically recognizable twinning on $\{02\bar{2}1\}$. Sometimes two sets of twin lamellae occur in one grain.

(i) *Preferred Orientation of $[0001]$.*—Text-fig. 5 is a profile of the

fold with the orientation diagrams for [0001]-axes in the three specimens superimposed. The orientation diagram for specimen 0.3 is also shown (McIntyre and Turner, 1953, text-figs. 6*b* and *c*). In all diagrams, including the one for the dolomite rock, there is a maximum concentration of [0001]-axes near the pole of the foliation (S_2). Such a preferred orientation has commonly been observed in marbles.

The preferred orientation of [0001]-axes of calcite and dolomite is thus inhomogeneous with respect to the fold; in other words, the fold can be "unrolled" (Sander, 1951), to produce a more homogeneous preferred orientation which may have existed previously. This contrasts strongly with the preferred orientation of quartz in the fold previously described; unrolling of that fold will not restore a homogeneous preferred orientation.

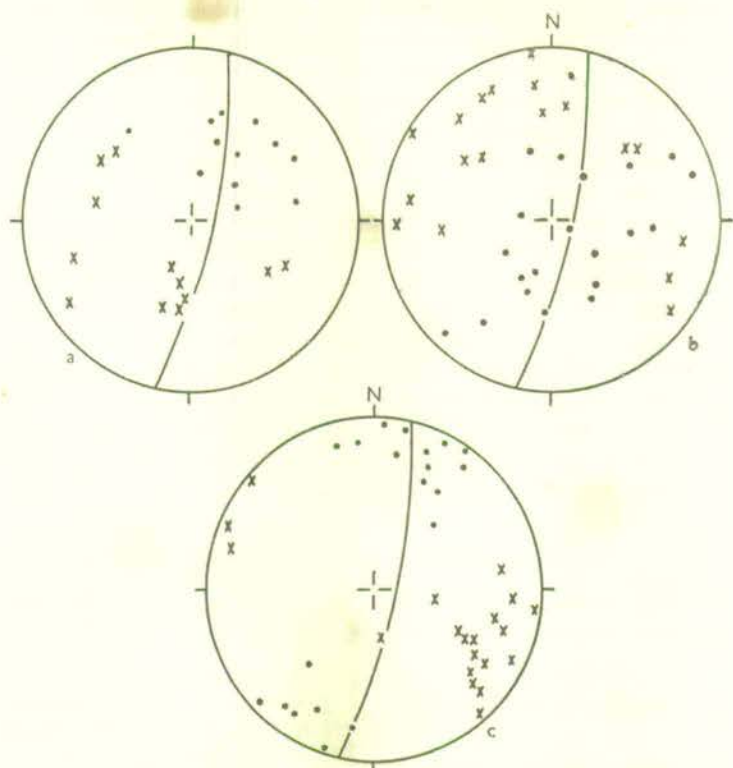
The symmetry of the fold is markedly monoclinic and the fold-axis is a B -axis. The symmetry of the diagrams is not readily determinable; there are no ac -girdles of [0001]-axes, and there is no marked plane of symmetry in the diagrams normal to the fold-axis. It is difficult to say whether or not the preferred orientation of [0001]-axes reflects the symmetry of the fold; it is not likely that it does since unrolling of the fold produces a more homogeneous preferred orientation. It is more likely that the preferred orientation of [0001]-axes was formed previously to and independently of the fold (cf. Weiss, 1954*A*, 1954*B*).

(ii) *Phenomena of Twinning.*—The twinning in the rock has been assumed to be a result of deformation and has been dynamically interpreted in the manner first described by Turner (1953). Points of compression and tension most favouring the twinning observed on {01 $\bar{1}$ 2}-lamellae in the calcite-marbles and on {02 $\bar{2}$ 1} in the dolomite rock have been constructed. The diagrams so prepared for specimens 1, 2, and 3 are shown rotated into geographical horizontal in Text-figs. 6*a*, *b*, and *c* respectively.

The most pronounced maxima of points of compression and tension are given by specimen 3, the dolomite rock. This is probably because the stress required to produce twinning in dolomite is greater than that required to produce twinning in calcite (Turner, Griggs, *et al*, 1954), and only lamellae upon which the maximum resolved shearing stress is very high would twin in the dolomite. In the calcite-marble {01 $\bar{1}$ 2}-planes with lower maximum resolved shearing stress would be active twin-planes under the same applied stress, thereby weakening the pattern of preferred orientation of stresses.

In general the points of compression for the three specimens lie in a vertical plane striking N.N.E.–S.S.W. The directions of applied stress necessary to produce the twinning would thus lie roughly in the ac -plane of B_2 , the axis of the fold, which, as determined in the field, plunges 10–12° towards N. 282°. In two specimens (Text-figs 6*b* and *c*)

the tension-axes show a preferred orientation parallel to the fold-axis; in the remaining specimen (Text-fig. 6a) they tend to lie in the *ac*-plane normal to the compression maximum. The orientation of tension-axes in this specimen may be a reflection upon its position near the hinge of the fold (Text-fig. 5b). At such a point the tension is more likely to lie in the *ac*-plane. Specimen 0.3, a calcite-marble



TEXT-FIG. 6.—Points of compression (dots) and tension (crosses) constructed for twin lamellae in (a) specimen 1, (b) specimen 2, and (c) specimen 3. Great circle is *ac*-plane related to B_2 .

described by McIntyre and Turner (1953), has grains characterized by very pronounced twinning. In the majority of grains it is impossible to distinguish between the initial and the twinned lattice. McIntyre and Turner concluded that many of the grains are more than half-twinned and they constructed a direction of compression from the maximum concentration of $[0001]$ -axes in apparently untwinned grains. This direction (43° towards N. 32°) also falls near the *ac*-plane of the fabric. The preferred orientation of compression-axes in the *ac*-plane of the fabric in all of the specimens suggests strongly that the

twinning has been produced during the folding and deformation about B_2 .

It is interesting to note that in the vertical limbs of the fold the effects of the stresses responsible for twinning seem to have been greater than in the horizontal limb. In the calcite-marble (specimen 0.3) it has produced almost complete twinning, and in the dolomite rock (specimen 3) it has produced pronounced twinning. In specimens 1 and 2 from the horizontal limb, only few and weak twin-lamellae occur in the calcite. These specimens with weak twinning give additional evidence that the preferred orientation of [0001]-axes may antedate the folding. The system of stresses indicated by the twinning is oriented in the deformation-plane of the fabric (according to Sander the symmetry-plane is the deformation-plane in a fabric with monoclinic symmetry). This deformation-plane is related to the movements about B_2 , yet it shows incipient re-orientation of [0001] in the twinned grains to form a vastly different pattern to the one present. If the [0001] orientation was produced by the movements about B_2 , it was produced in an earlier phase by stresses of greatly different orientation. In specimen 0.3 (Text-fig. 5a) the [0001]-orientation pattern approaches the form of an *ac*-girdle around B_2 . This orientation supports the suggestion of McIntyre and Turner (1953, pp. 238–9) that at least some of the [0001]-axes in this rock have been oriented in response to movements about B_2 .

IV. SUMMARY AND CONCLUSIONS

The contrasted features of the two styles of folding described above are summarized in the following table:—

<i>Folding about B_1.</i>	<i>Folding about B_2.</i>
(1) Superposed recumbent folds .	Folds with one horizontal and one vertical limb, the axial-plane dipping towards the north.
(2) North-south trend	East-west trend.
(3) S_2 unfolded	No unfolded S found.
(4) No evidence for folding by flexural-slip.	Folding by flexural-slip.
(5) Strong lineation parallel to fold-axis.	Lineation weak or absent.
(6) Non-unrollable with respect to preferred orientation of [0001] in quartz.	Unrollable with respect to preferred orientation of [0001] in calcite and dolomite.
(7) Found only in quartzite	Found in mica-schist, granulite, and marble.
(8) Involved mylonitization and streaming in B_1 , followed by recrystallization of quartz.	No evidence for mylonitization, streaming, or extensive crystallization after folding about B_2 .
(9) Could have been produced by movements with orthorhombic symmetry.	More likely to have been produced by movements with monoclinic than orthorhombic symmetry.

(a) Relationship of the Two Styles in Space

Folds about B_1 and B_2 are closely associated in space, separated only by a thin micaceous layer on which there has been *décollement* of the overlying beds during folding about B_2 (see Text-fig. 3). Movement was thus concentrated in this layer which separates rocks of greatly differing competence. Concentration of movements in narrow zones in complexes of deformed rock is a common phenomenon (Weiss, 1954A, pp. 4-5). The kinematic principles underlying the production of these "movement-horizons" have been discussed by Knopf (1938, pp. 33-5). She has emphasized that "*The smaller the participating elements in relation to a whole deformation the slower is the rate of differential movement necessary to produce a given change in shape in a given time*" (Knopf's italics). Knopf also points out, following Sander, that if movement is on the ionic scale (indirect componental movement), then "crystalloblastesis may predominate over cataclasis even in zones of intense differential movement. . . . Microscopic investigation is gradually bringing to light zones where intense differential displacement has been carried by elements that are so small in comparison with the size of the whole that the deformation is essentially continuous and the tectonic displacement large".

Displacement along a movement-horizon is by continuous deformation involving no rupture. The small thickness of rock, relative to the whole deformed mass, in which the movements are concentrated can in no way be thought of as a fault. The slides described by Bailey in the Scottish Highlands (1910, p. 593; 1909, pp. 53-4) appear to be movement-horizons of this type. Bailey has classified slides as faults, thereby implying that they originate by fracture. However, in a personal communication, he agrees that the term slide was intended to cover movement-horizons of the type described above.

The close proximity of folds about B_1 and B_2 with no axial-structures of intermediate trend between, suggests that the two axes are distinct. The β -diagram (Text-fig. 2c) prepared from an area of the mica-schist, granulite, and marble series immediately overlying the quartzite, and showing no B -structures, contains a diffuse maximum in the north-west quadrant. The uniform attitude of the layers involved forbids precise interpretation of the maximum.

(b) Relationship of the Two Styles in Time

Whereas the movements about B_1 are intensely penetrative and homogeneous, those about B_2 are hardly penetrative and inhomogeneous. A quartzite with fibrous structure is likely to survive slightly

penetrative folding around B_2 , normal to the fibrous structure, because, without initial planar structures tautozonal about the axis of folding, flexural-slip folding is an impossibility. On the other hand layers of weakly folded marbles and mica-schists are unlikely to survive unaffected the intensely penetrative movement responsible for the folding of the quartzite about an axis, B_1 , lying subparallel to the layers.

In an account of the fabric of the schists of the "Penmynydd Zone" of metamorphism, Anglesey, one of us has pointed out that "isolated intraformational folds sometimes preserved within fine-grained quartz-schists . . . suggest that in localized 'sheltered' areas . . . earlier planar structures, perhaps bedding, perhaps foliation produced under different dynamic conditions, may be found preserved" (Weiss, 1953, pp. 109 and 115). The presence in the folded quartzite of micaceous cores, with unfolded S_2 , suggests that the uniform layering of the mica-schist, granulite, and marble series may have been produced by the movements which formed the folds about B_1 . If this is so, i.e. if $S_3 = S_2$, then folding of S_3 about any axis other than B_1 must have occurred later than the formation of S_3 and the operation of B_1 .

(c) *Regional Significance*

Systems of so-called double-folding have been postulated for several areas in the Scottish Highlands. The recognition of these systems is based on the strike of foliation (see Phemister, 1948, pp. 22-3), and this method has already been criticized by one of us (McIntyre, 1952). Our recognition on Ord Ban of two B -axes, distinct in time, is based on geometric and kinematic analysis. The preservation of B_1 in the quartzite indicates that the tectonic history of the associated mica-schist, granulite, and marble has been highly complex. Perhaps, elsewhere in the Highlands, apparently simple structures in micaceous rocks may conceal complex histories.

On Ord Ban neither B_1 nor B_2 agrees in trend with what appears to be the regional fold-axis trending north-west-south-east. Many folds on the east side of the hill have an axis which trends in this direction, and have some of the characters of the folds about both B_1 and B_2 (e.g. McIntyre, 1951, Text-fig. 1). A study of these folds has not been included in our investigation. It appears to us that previous work has shown the complexity of Highland tectonics to be so great that detailed investigations of critical areas are necessary before a tectonic synthesis will be possible. The present study is intended as a contribution to our knowledge of one of these areas.

Some of the equipment used in this Research was purchased with the aid of a grant from the Moray Fund, University of Edinburgh.

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EXPLANATION OF PLATES I AND II

PLATE I.—(a) Recumbent fold in quartzite.

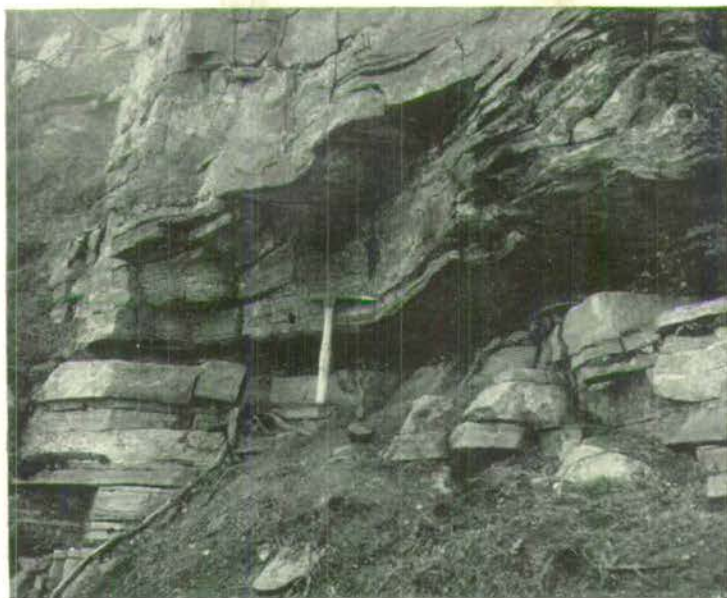
(b) Slide separating quartzite below from mica-schist, granulite, and marble series above. The slide is covered by the central portion of the hammer-handle. Monoclinial folds about B_2 can be seen in the schist series; the quartzite is exposed in Bc -section (axis of folding, B_1), and so appears to be unfolded.

PLATE II.—(a) Quartzite in ac -section under crossed nicols. The layer of small quartz grains is parallel to S_1 .

(b) Quartzite in ab -section under crossed nicols. The lines on the photomicrographs are 5 mm. in length.



a

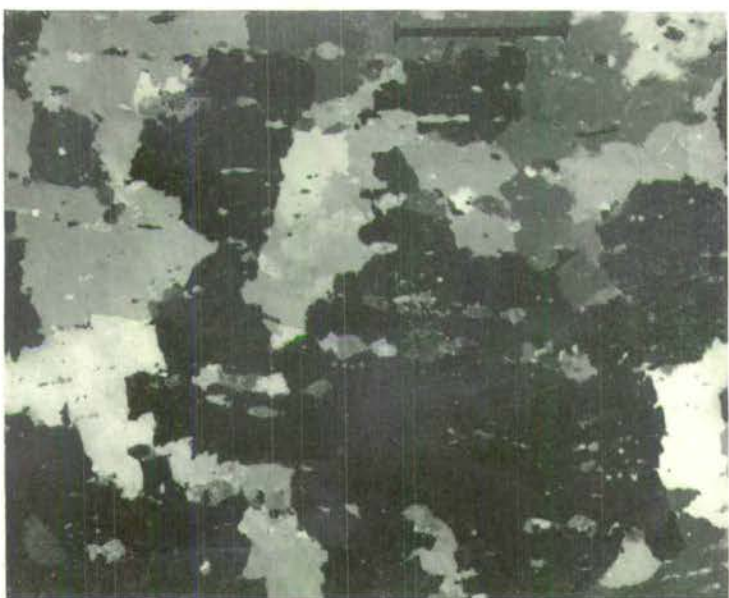


b

STRUCTURES IN THE ROCKS OF ORD BAN.



a



b

QUARTZITE OF ORD BAN.

I. 4. Construction to Scale of Block Diagrams
in Orthographic Projection.
(Jointly with D.B.McIntyre)

CONSTRUCTION TO SCALE OF BLOCK DIAGRAMS IN ORTHOGRAPHIC PROJECTION

Donald B. McIntyre and L. E. Weiss

ABSTRACT

The paper describes a simple method of constructing block diagrams to scale in orthographic projection by the use of an orthographic net. The procedure is illustrated by reference to an actual example of considerable complexity. An alternative construction using a stereographic net is also given.

INTRODUCTION

Block diagrams can be used effectively as illustrations of rock structures (e.g. Lobeck, 1924), and Goguel (1952, pp. 115-116) has described a simple construction for the representation of topographic relief in such diagrams. It is, however, the case that block-diagrams have seldom been used to show accurately and to scale the structure of a mass of rock. The main reason for this is that the scale of a block diagram varies in different directions and for each angle of sight; in point-perspective projections it is not constant/

constant even in any one direction. Accurate representation of distances and angles has therefore been supposed to be difficult (Billings, 1942, pp. 85-86).

The special case of an orthographic projection of a rectangular block, viewed from such an angle that all edges are foreshortened equally, has been discussed by Johnston and Nolan (1937), and isometric graph-paper to facilitate the construction is available commercially (e.g. from H. K. Lewis, 136 Gower Street, London, W.C.1. England). It is the purpose of this paper to show how a block diagram in orthographic projection may be constructed without difficulty, and for any required angle of sight, from given structural data, so that scales along every direction are known, and all faces of the block give accurate representations of the traces of the structures on them.

ORTHOGRAPHIC PROJECTION AND THE ORTHOGRAPHIC NET

A projection is orthographic if the lines of projection are mutually parallel and normal to the plane of projection. The perspective of the projection is such that the vanishing-point is at infinity, and all lines which are parallel/

parallel on an object remain parallel upon its projection.

An orthographic net can be prepared in the same manner as a stereographic net (see Hutchinson, 1908, pp. 105-112; Wright, 1916) by projection of lines of latitude and longitude on a hemisphere onto a plane containing the polar axis. The circles of latitude project as straight lines and the meridians of longitude as ellipses. The orthographic net compares closely with the view of a suitably inscribed and oriented sphere from a distance. It is the man-in-the-moon's view of the earth and our view of the moon. Because of this the orthographic net has been used for mapping planetary bodies; for instance, orthographic nets (sun-discs) for the determination of latitude and longitude of sun spots were formerly published for the Stonyhurst Observatory by Casella and Co. Another interesting application of the projection is in the calibration of sun-dials. F.E. Wright (1907, 1911, & 1913) has pointed out that interference figures are orthographic projections of interference phenomena in space, and has published nets of 10 cm (1907) and 20 cm (1911) diameter. We have reproduced a reduction of/

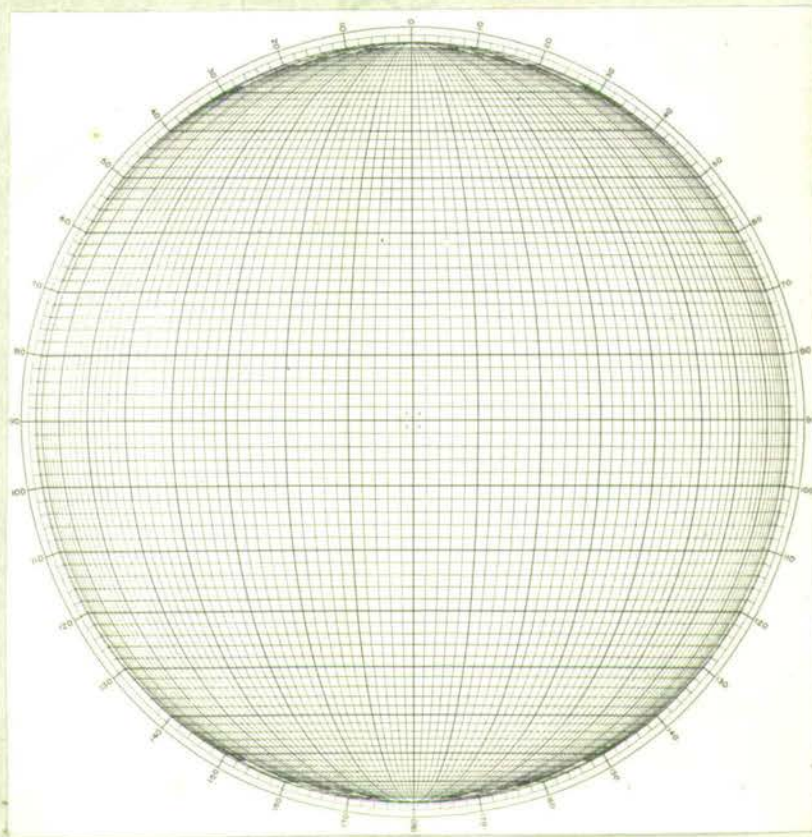


Figure 1. Orthographic net, based on Wright, 1911, plate 4, with permission of the Trustees, Carnegie Institute of Washington.

of Wright's 20 cm net in figure 1.

Hilton (1917a & b) has published methods of rotation (without the use of nets) on orthographic, gnomonic, and stereographic projections; and Wright (1932) has also contributed to this subject. The equations for great and small circles in these three projections, as well as in two related projections, have been given by Wright (1929); see also Hilton, 1903, 1904, 1917a & b).

Hilton (1904, & 1917b; see Barker, 1922, p. 48, footnote) has shown how to determine directions of crystal edges in orthographic projection from gnomonic and stereographic nets. He was also the first to point out that the orthographic net was the proper net for constructing drawings of crystals in orthographic projection. He developed a very simple method of making such drawings (1917a, figure 4) and of constructing any given axial cross. This method is the basis of the construction given by Barker (1922, pp. 49-54) and Phillips (1946, pp. 214-218).

The three projection-nets, gnomonic, stereographic, and orthographic, are closely interrelated and can be derived one/

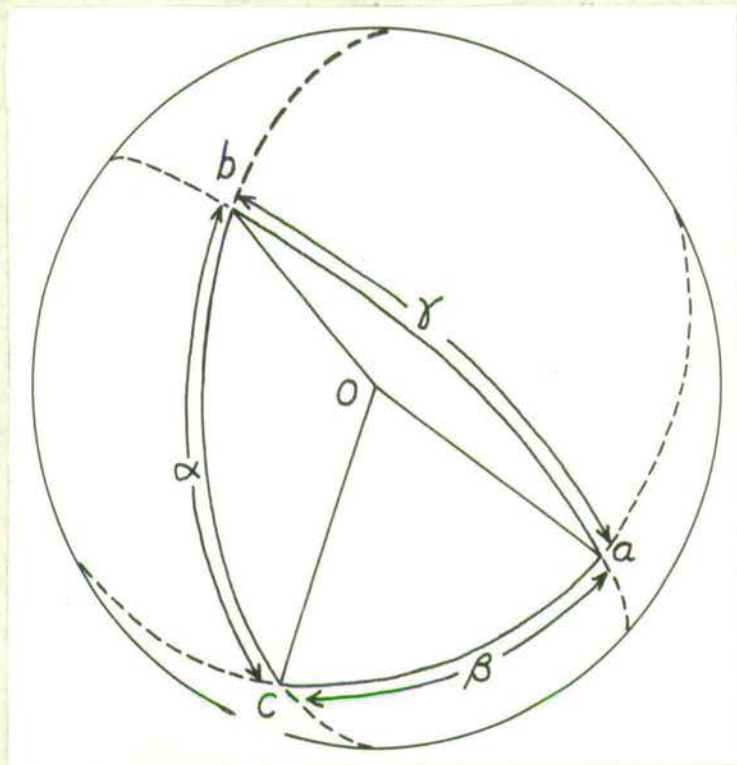


Figure 2. Orthographic projection of three axes, a , b and c , intersecting at O . The angles α , β and γ define their relative orientations.

one from another. The method of transposing a point on a stereographic net into its equivalent position on an orthographic net is described below.

USE OF ORTHOGRAPHIC NET IN CONSTRUCTING AN AXIAL CROSS

Since all points on the fundamental sphere are at the same distance from the centre of the sphere, lines joining any points on the projection-net to the centre of the net are projections of lines of equal length. The three points a, b & c, (figure 2) are thus the projections of three mutually inclined lines of equal length meeting at point O. The angles α , β , & γ between the lines can be read off along the arcs of the great circles¹ shown. The three lines thus enclose a solid angle, seen in orthographic projection, at a definite inclination to the plane of projection.

From figure 2 it will be seen that it is possible to construct/

¹On the orthographic net the great "circles" are ellipses.

Since, however, these are projections of great circles on the fundamental sphere, they will be referred to throughout this paper as great circles.

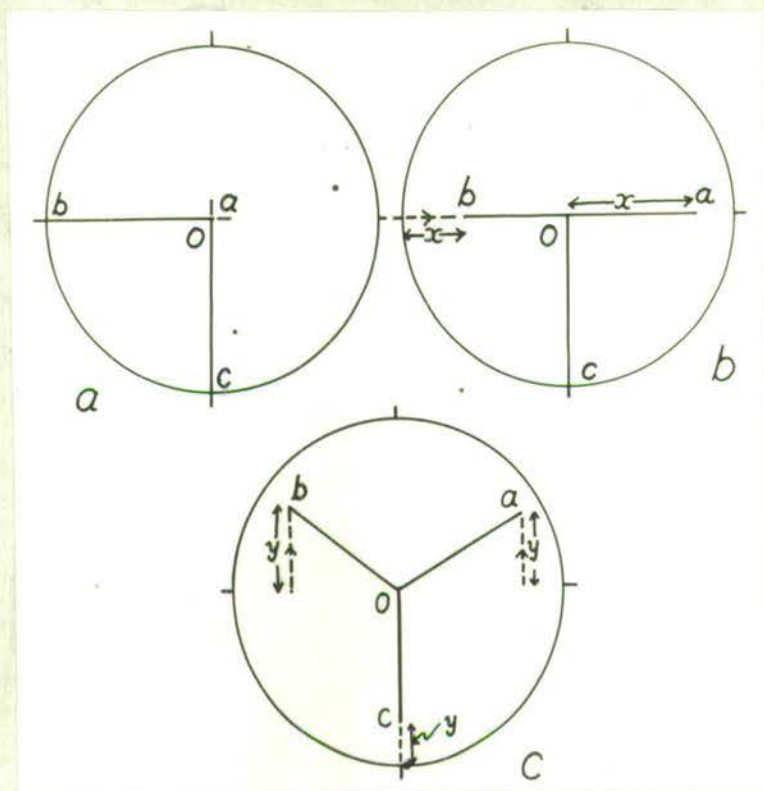


Figure 3. Orthographic projection, lower hemisphere, of three orthogonal axes, a , b and c , intersecting at O .

- a. Projection on bc -plane.
- b. Rotation of x^0 about north-south diameter.
- c. Rotation of y^0 about east-west diameter.

construct an axial cross, consisting of any number of lines at any given inclinations to each other and to the plane of projection, so that unit length along each line is accurately known. An example we shall consider the axial cross which will usually be required for a simple block diagram; viz. three mutually perpendicular axes at an angle to the plane of projection dependant on the angle of sight chosen. From such an axial cross it will be possible to construct a rectangular block in orthographic projection.

In order to see all three faces of the block, the orthogonal axes forming its edges must all be inclined to the plane of projection. Also, since it is common practice for one edge to be vertical and the top surface visible, the axial cross will be plotted in the lower hemisphere of the projection. The net is oriented with its polar diameter in the east-west position. The inclinations to the plane of projection of the three axes, a, b, & c, is best described in terms of rotation about the east-west and north-south diameters of the projection-net (figure 3). The three axes are shown (figure 3a) projected/

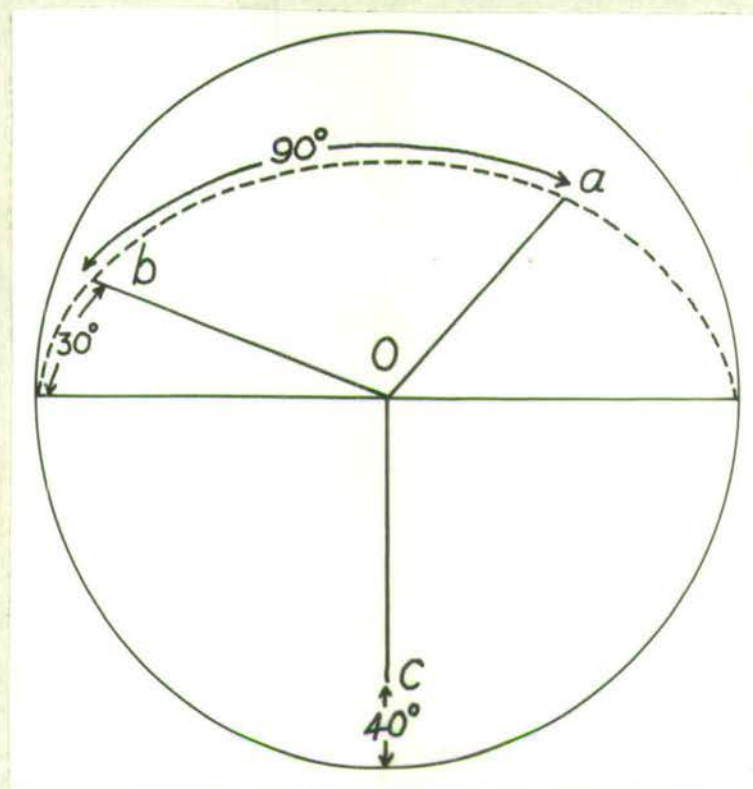


Figure 4. Orthographic projection, lower hemisphere, of three orthogonal axes, a , b and c , intersecting at O ; $x = 30^\circ$, $y = 40^\circ$.

jected along a line parallel to a; b & c lie in the plane of projection. The axes are first rotated through an angle, x, around the north-south diameter of the net, so that b moves away from the primitive circle and a from the centre of the projection (figure 3b). A second rotation (y) around the east-west diameter inclines the plane a-b and displaces c from the primitive circle (figure 3c). All three axes are now inclined to the plane of projection according to the given angles x and y. The choice of x and y will depend primarily upon the relative importance of the data to be represented on each face.

To show how the construction can be made directly, without the intermediate steps shown in fig. 3 a & b, we shall consider an example in which $\underline{x} = 30^{\circ}$ and $\underline{y} = 40^{\circ}$ (figure 4). Oc can be drawn along the north-south diameter of the net so that c is 40° from the primitive circle. The trace of plane ab is given by the great circle of which c is the pole. b and a lie on this great circle; b 30° from the primitive circle and a 90° from b, measured along this great circle. The positions of all three axes are now determined. Also, since the lines on the/

the net are projections of lines of equal length, we know the scale along each axis.

For three axes mutually inclined at angles other than 90° , the procedure is similar, although it is simpler in such cases to make the rotations through x and y as separate steps. To achieve a required final inclination of the axes to the plane of projection, the values of x and y will depend upon the initial position from which these rotations are to be made. If the three axes are labelled a, b, and c, the initial position should be with c lying on the primitive circle at the equatorial diameter and either the plane ac normal to the plane of projection, or the plane bc parallel to it.

CONSTRUCTION TO SCALE OF A BLOCK DIAGRAM FROM GIVEN DATA

To illustrate the method of constructing a block diagram from an axial cross, and actual example will be taken (Weiss, McIntyre, & Kursten, 1954). The following data are given:

A series of granulites and mica-schists above, is separated from/

from a body of quartzite below by a layer of mica which marks a slide. The granulite and mica-schist series is folded in small monoclinal folds which have the slide as a plane of decollement. The axial surfaces² of these monoclines are parallel planes striking 70° and dipping $56^{\circ}N$. The axis of the folds (B_2) trends 257° and plunges $9^{\circ}W$. The quartzite below the slide is folded in superposed recumbent folds about an axis (B_1) trending 348° and plunging $6^{\circ}N$. The axis is paralleled by a marked lineation defined by the alignment and elongation of small grains. The axial surfaces of the folds are parallel planes striking 22° and dipping $11^{\circ}W$. In the micaceous layers a foliation is developed parallel to the axial-surface of the folds.

S_1 foliation in quartzite folded about B_1 .

S_2 foliation in micaceous layers in quartzite, parallel to the axial surface of folds about B_1 .

S_3 foliation in granulite-mica-schist series folded about B_2 .

S_4 the slide, parallel to S_2 and containing B_1 and B_2 .

In/

²For discussion of the terms fold-axis, profile, hinge, and axial-surface, see Clark and McIntyre, 1951a.

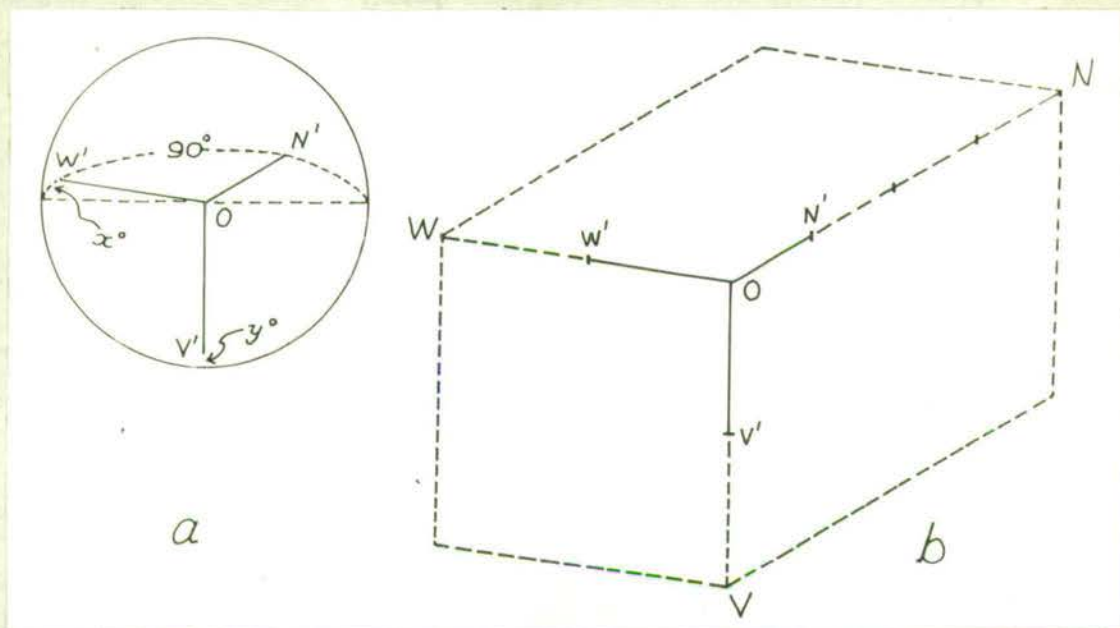


Figure 5. Construction of a diagram of an orthogonal block, edges $1 \times 1 \times 2$, seen in orthographic projection; viewpoint given by x and y .

In the field, sketches were drawn to scale from faces of known orientation, to show the form and dimensions of the structures in two dimensions.

A block diagram is to be constructed in the form of a square (tetragonal) prism, of length equal to twice the side of the square face, and oriented with the long edges north-south and the short edges vertical and horizontal respectively. The angles of rotation of the plane of projection from a vertical east-west plane (parallel to the square face of the block) are $x = 28^{\circ}$, and $y = 18^{\circ}$. The axial cross of the block is constructed as described above (figure 5a). The three lines OW', ON', and OV' are oriented east-west, north-south, and vertically respectively. These lines are traced onto another sheet and form one corner of the block in orthographic projection. Moreover, since these three lines are projections of lines of equal length, we have the scale along each, and we can construct the block by means of a parallel rule. From the initial three lines, whose actual lengths will depend upon the diameter of the orthographic net used, it is possible to construct the block to any actual size and with any/

any required habit. The block diagram shown in figure 5b has been constructed so that $OW = 2OW'$, $OV = 2OV'$, and $ON = 4ON'$. The block has thus the required dimensional ratios.

Onto this outline block diagram, the form and relative dimensions of the structure to be represented must now be transferred in correct orientation and perspective from the field sketches. The complex example we are considering is unusual in that field sketches made from two differently oriented faces have to be employed. The reason for this is that we are dealing with two systems of folding about axes which are nearly mutually perpendicular. Generally a block diagram will be constructed from one field sketch only. In order to make an accurate construction from two or more field sketches, these should have a point in common. In the present example they merely have a plane in common (\underline{S}_4). This plane has the same orientation in the adjacent localities from which the sketches were prepared, and in order to construct a block including both localities the portion above \underline{S}_4 has been moved slightly southwards along \underline{S}_4 with respect to the portion below \underline{S}_4 .

One/

One of the field sketches shows the form and relative dimensions of folds about \underline{B}_1 , the other of folds about \underline{B}_2 . Both sketches include \underline{S}_4 . The faces sketched are neither normal to the fold-axes nor parallel to any face of the block. However, since the trend and plunge of both fold-axes are known, it is possible to project the sketches onto planes parallel to any face of the block. Face WOV is nearly normal to \underline{B}_1 so the sketch showing folds about \underline{B}_1 will be projected onto this plane as viewed normally. Similarly, face VON is almost normal to \underline{B}_2 , and the sketch showing the folds about this axis will be projected in the same manner parallel to \underline{B}_2 . In the particular case described below there are exposure-surfaces which are nearly parallel to faces of the block. Since only a small correction is required in the field-sketches to effect their projection on to these faces, we shall describe the procedure to be employed in a hypothetical general case.

Example illustrating the general case of axial-projection; i.e. projection from one plane to another not at right angles or parallel to the first, both planes being oblique to the fold-axis. In the stereographic projection (figure 6), the orientations/

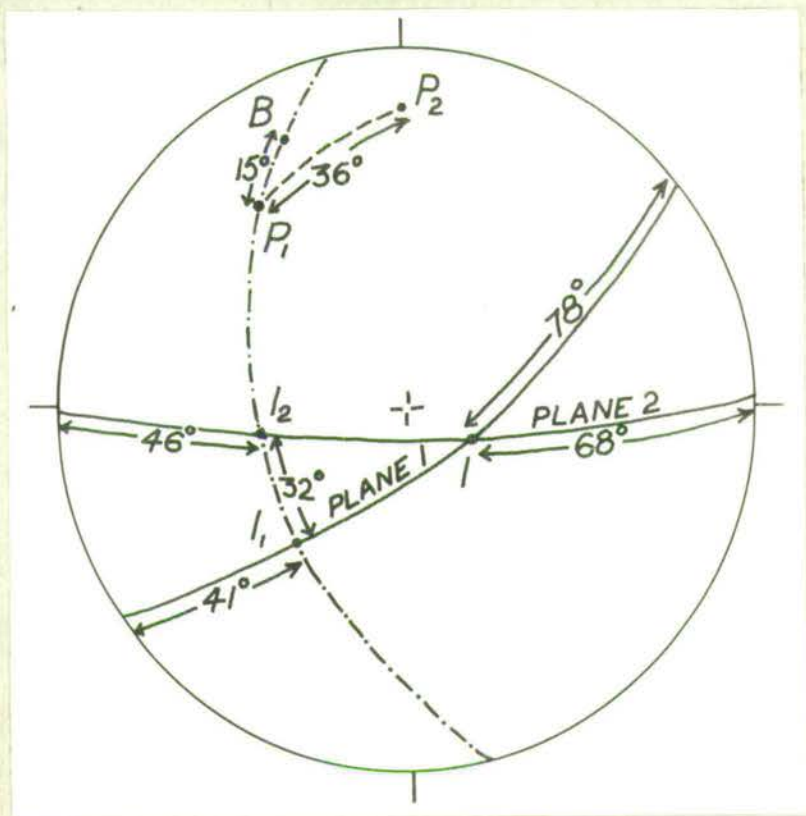


Figure 6. Stereographic projection (lower hemisphere) of plane 1 (pole = P_1), plane 2 (pole = P_2), and fold axis (B). Planes 1 and 2 intersect at I. The plane B- P_1 intersects plane 1 at I_1 and plane 2 at I_2 .

orientations of Planes 1 and 2 and of the fold-axis are given. It is required to project, parallel to \underline{B} , traces of form-surfaces³ from Plane 1 onto Plane 2. Figures 9 a, b and c represent Plane 1, Plane 2, and the Plane containing \underline{B} and the normal to Plane 1 (i.e. \underline{P}_1) respectively; in each case the planes are viewed normally and the necessary angular relations can be read from fig. 7.

X-Y (i.e. \underline{I}) is common to Planes 1 and 2;

L-M (i.e. \underline{I}_1) is common to Planes 1 and $\underline{B-P}_1$; and

L-N (i.e. \underline{I}_2) is common to Planes 2 and $\underline{B-P}_1$.

It follows that the point \underline{p} on Plane 1 projects parallel to \underline{B} to the position \underline{c} on Plane 2. It is thus a simple matter to draw a grid on Plane 1 (the axes of the grid being parallel to X-Y and L-M respectively) and to construct the equivalent grid on Plane 2 (the axes being parallel to X-Y and L-N respectively). Units on X-Y remain unchanged on the two planes. A distance \underline{s} on L-M becomes \underline{t} on L-N, where $t = s \cdot \sin 75^\circ / \sin 73^\circ$.

³A form-surface is any surface selected to outline the form of a structure. It is analogous to a surveyor's form-line, i.e. a contour of unspecified altitude, usually drawn in by eye in the fields.

$\sin 73^\circ$. The necessary data consists of six angles which can all be read directly from a stereographic net by plotting three great circles.

On the block diagram in orthographic projection, the faces are not viewed normally, but since the scales have already been determined, it is easy to prepare the necessary grids to distort the sketches into orthographic projection so that they can be transferred to the appropriate faces of the block. It is then possible to complete the block diagram by construction on the orthographic net.

The successive hinges of one fold will intersect a given face along the trace of the axial-surface of the fold on that face. As an example of the construction a fold about B_1 , seen on WOV, and closing to the east about half-way down VO will be considered. We require the closure of the form-surfaces on VON. Since B_1 trends west to north, the closures appearing on VON will belong to form-surfaces with hinges passing to the east of edge VO; i.e. on the plane parallel to WOV these hinges will appear to the east of VO. The field sketch must therefore include data from beyond the extent of/

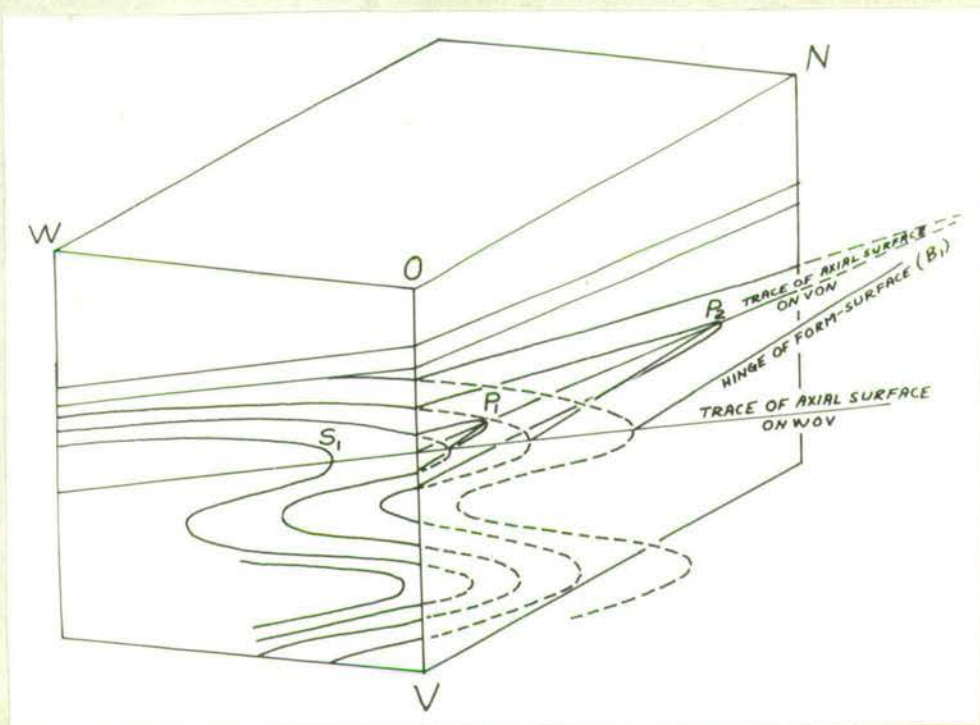


Figure 8. Projection parallel to B_1 of hinges observed on WOV onto VON.

of the face WOV. The folds concerned are shown in orthographic projection in figure 8. The hinges of successive form-surfaces intersect the trace of the axial-surface of the fold at points P_1 , P_2 , and so on. The trace of the axial-surface on VON can be determined on the orthographic net; the axial-surface and the face VON are plotted as great circles and the line joining their point of intersection to the centre of the net is the required trace (fig. 10), which can be transferred directly to the block. The hinge of any form-surface is parallel to B_1 ; this can be plotted as a point on the net and joined to the centre to give a direction which may be transferred to any position in the block diagram as the orthographic projection of B_1 (figure 9). In this manner all the closures of S_1 falling on VON can be plotted accurately.

To find the traces of the folds about B_2 on faces other than VON, the same procedure is followed using the known orientation of the axial-surface of these folds and the known trend and plunge of B_2 . The various traces required in the construction/

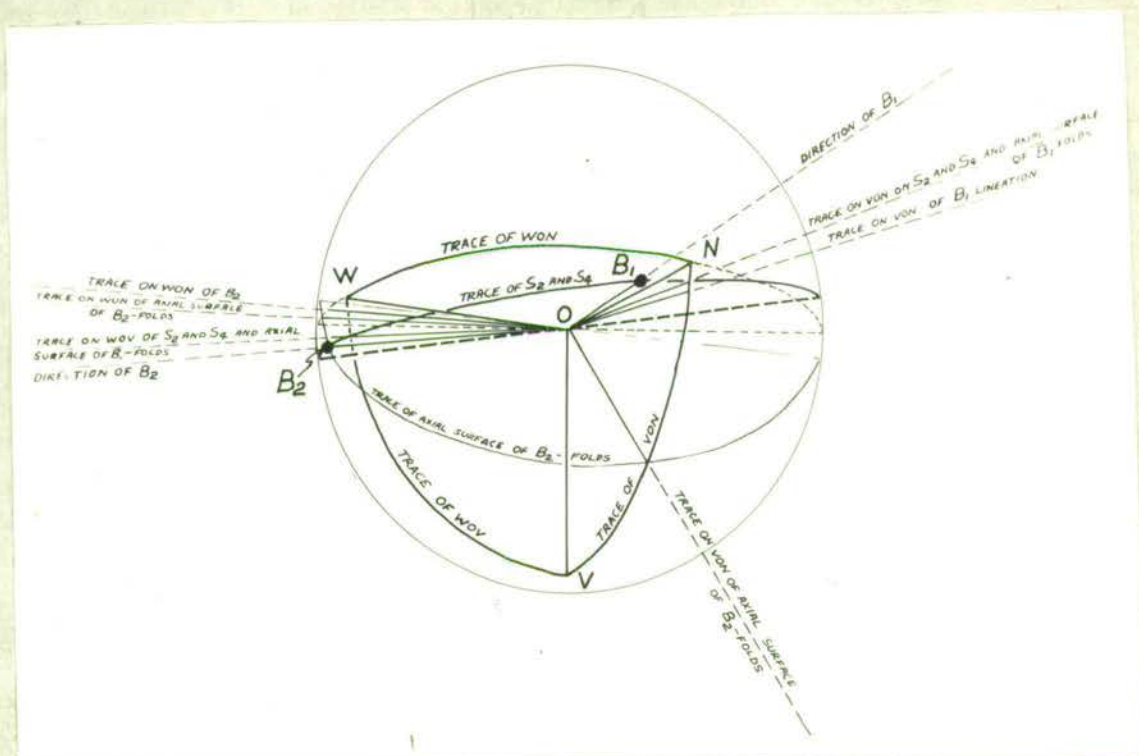
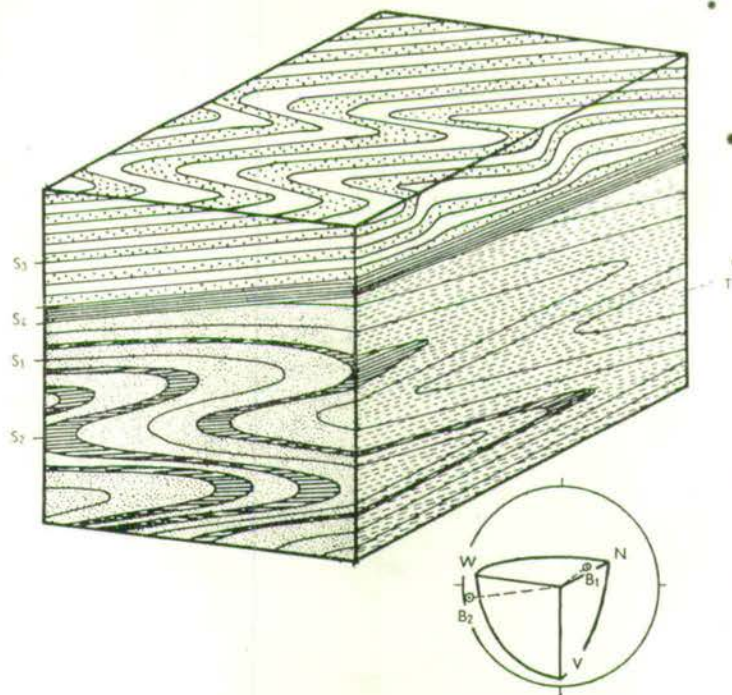


Figure 9. Orthographic projection, lower hemisphere, showing data necessary for construction of block diagram, figure 10.

construction are again determined on the orthographic net (figure 9) and transferred directly with the aid of a parallel rule to the block diagram. When all the closures have been determined, the traces of the form-surfaces are drawn in on the three faces of the block diagrams.

All that remains to be inserted in order to complete the diagram is the trace of \underline{S}_2 on WOV and on VON (\underline{S}_2 is parallel to \underline{S}_4), and the trace of the lineation parallel to \underline{B}_1 on VON. The latter lies in the plane normal to VON containing \underline{B}_1 (Lowe, 1946; Clark and McIntyre, 1951b). The direction of the trace can be determined on the orthographic net (figure 9) and transferred directly to the block diagram. \underline{B}_1 is so nearly normal to WOV that the lineation parallel to \underline{B}_1 will leave no visible trace. There is no lineation parallel to \underline{B}_2 to leave a trace on WOV or on WON. The completed diagram is shown in fig. 10.

Block diagrams of the kind described can be constructed in any shape or orientation. Also, the block may be parted along any given plane to assist a three dimensional/



-Relationship of planar and linear structures on either side of the slide separating the quartzite from the mica-schist, granulite and marble series.

S_1 micaceous laminae and layering in quartzite.

S_2 axial-plane foliation of micaceous cores in quartzite.

S_3 foliation of the mica-schist, granulite, and marble series (separated from the quartzite by the slide).

S_4 foliation developed in micaceous layer along zone of movement.

T trace of B_1 -lineation.

W, west; N, north; V, vertical downwards.

Figure 10. Completed block diagram; construction described in text.

sional appreciation of the structures, and the angle of sight can be changed by simple rotation of the orthographic net. Conversely to the construction described, it is possible, given a block diagram in orthographic projection, to read from the net the angle of sight and the scale along any direction in the diagram.

ALTERNATIVE CONSTRUCTION USING A STEREOGRAPHIC NET

If no orthographic net is available, all data can be plotted on a stereographic net and the relevant points transposed by a simple construction into the equivalent position on an orthographic net. The construction is shown in figure 11. Point S (figure 11a) has been plotted on a piece of tracing paper over a stereographic net. To transpose it to the equivalent point in orthographic projection, the tracing paper is rotated until the point lies on the polar diameter of the stereographic net (PP' in figure 11b). From the intersection, S', of the primitive circle with the small circle through S, a normal is drawn to the polar diameter. The point of intersection/

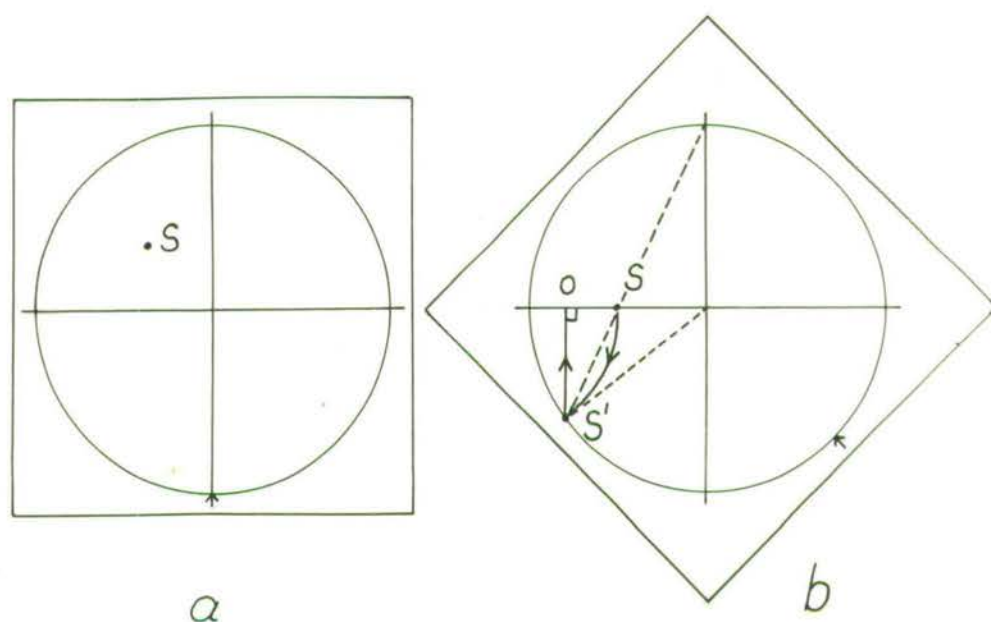


Figure 11. Transposition of point S in stereographic projection into equivalent point, O , in orthographic projection.

section, O , is the required position of S in orthographic projection. This simple construction can readily be understood if figure 11b is considered as a section of the fundamental sphere normal to the plane of projection (see Sommerfeldt, 1906).

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1. 5. Fabric Analysis of a Triclinic Tectonite
and its Bearing upon the Geometry of
Flow in Rocks.

FABRIC ANALYSIS OF A TRICLINIC TECTONITE AND ITS BEARING ON THE GEOMETRY OF FLOW IN ROCKS

L. E. WEISS

ABSTRACT. A triclinc tectonite from Anglesey showing asymmetrically oriented quartz and mica girdles is analyzed geometrically and kinematically. Some important features of the geometry of plane deformations with monoclinic symmetry are emphasized and discussed; and on the basis of these principles the fabric of the triclinc tectonite is interpreted in terms of one monoclinic deformation involving solid flow. It is concluded that a descriptive geometrical analysis on all scales must precede kinematic interpretation of fabric data.

INTRODUCTION

Fabric analysis of *B*-tectonites has demonstrated the existence of a commonly occurring type of fabric in which a single girdle of {001}-poles of mica, agreeing in symmetry with the main features of the megascopic fabric, is oriented asymmetrically with respect to an accompanying single girdle of [0001]-axes of quartz (Sahama, 1936; Turner, 1940; Wenk, 1943; Phillips, 1945; Kvale, 1953). With the possible exception of the granulite described by Sahama—in which the symmetry is dominantly orthorhombic—in these fabrics, generally, an apparent monoclinic symmetry defined by the megascopic fabric and the preferred orientation of mica is lowered to triclinc symmetry by the preferred orientation of quartz. The non-coincidence of the axes of the girdles has been universally interpreted to mean that the preferred orientation of mica and quartz has been effected by differently directed movements. Phillips (1945, p. 216) writes, with reference to the microfabric of the Moine schists: "Study of geographically oriented diagrams, however, shows that there is frequently a slight discordance between the attitude of the mica girdles on the one hand and the quartz girdles on the other in diagrams for the same section." Phillips goes on to suggest that this anomaly may indicate the effects of later movements upon an already existent preferred orientation of quartz. Kvale (1953, p. 60) likewise records discrepancies: "In some rocks, if the megascopic lineation deviates from the principal direction of movement (east-south-east) the micas form a girdle with the megascopic lineation as the *b*-axis, while the quartz axes form a girdle around an axis trending about east-south-east. This seems to indicate that the quartz grains reflect a later stage of deformation than do the micas." Neglecting Kvale's interpretation of the girdles and his views on the importance of fabric symmetry, it should be noted that he records quartz girdles more constant in orientation than either the associated megascopic fabric or the mica girdles. The writer has observed a similar phenomenon in southern Anglesey, a possible explanation of which will be outlined later in the paper.

In general, in such fabrics, each girdle is symmetrologically an *ac*-girdle for the fabric component concerned; and associated lineations lying in the foliation are symmetrologically *B*-lineations. The rocks are generally interpreted as $B \wedge B'$ -tectonites, with one *B*-axis (*B*) parallel to the main lineation and axis of the mica girdle, and the other, later *B*-axis (*B'*), parallel to the

axis of the quartz girdle. Movements about B' , it has been argued, were insufficiently strong to reorient the mica fabric and destroy the symmetry of its megascopic manifestation (foliation, lineation and folds). The interpretation implies that quartz can acquire a marked preferred orientation in response to deformation with little or no movement in the fabric; and this view has become generally held in spite of the absence of supporting evidence of any kind.

This paper presents the results of fabric analysis of one such " $B \wedge B'$ -tectonite" from near Gaerwen in Anglesey (N. Wales), analyzed during a regional study of the fabrics of the Penmynydd schists. The orientation data are interpreted by the writer in terms of a single symmetry-constant movement involving solid flow. Similar interpretations may be possible for some, but not necessarily all, similar triclinic $B \wedge B'$ -fabrics referred to in the opening paragraph.

PRELIMINARY DISCUSSION

Monoclinic flow in rocks.—For the purpose of this paper we consider only the type of deformation which has been called rotational strain (Becker, 1893) and which is referred to more generally as slip upon one set of parallel s -surfaces (Knopf and Ingerson, 1938, p. 75-77; Turner, 1948, p. 164-166).¹ This is a plane deformation with monoclinic symmetry of movement. The deformation plane is the symmetry plane of the movements and is also the symmetry plane of the structures *newly* produced by the movements.

For rotational strain to occur, the resolved shear stress on the slip plane must exceed the resistance to shear (shear strength) on that plane. Since pre-existing s -surfaces of many sedimentary and metamorphic rocks are planes of relatively low shear strength, it is to be expected that they will commonly function as initial slip surfaces, even when the resolved shear stress acting upon them is somewhat less than the maximum possible value. In other cases, the pre-existing s -surfaces are so oriented in the field of stress that resolved shear stress upon them is too low for slip to occur. Slip must therefore take place upon some other plane upon which the resolved shear stress is high. The mode of development of this newly induced slip plane lies somewhere between two extremes:

1. Slip is concentrated upon parallel discrete surfaces separating layers of relatively undeformed material, as in displacement of a pack of cards. The slip surfaces are visibly expressed as strain-slip or fracture cleavage.
2. Slip is more or less evenly dispersed throughout the deformed rock even on a microscopic scale. Intragranular gliding and recrystallization are important componental movements, and the rock behaves "plastically."² Although no discrete individual surfaces of slip develop, the deformation still can be pictured in terms of slip upon a definite plane, or of slip upon surfaces spaced infinitesimal distance apart. The geometry of the deformation ap-

¹ Nonplanar deformations involving solid flow with triclinic symmetry are beyond the scope of this paper.

² For a discussion of this usage of the term *plastic* see Knopf and Ingerson, 1938, p. 179-189; Turner, 1948, p. 225-237; and Fairbairn, 1949, p. 96-115.

proximates to that of plastic flow in a crystal or laminar flow in a fluid (Knopf and Ingerson, 1938, p. 33-36).

s-surfaces and s-planes.—The planar elements that are so characteristic of the fabrics of rocks have been termed *s-surfaces* (*s-flächen*) by Sander (1948, p. 105-107). Those produced by deformation are, as we have just seen, of two extreme types which, although grading one into the other, may conveniently be distinguished. In this paper they are respectively designated *s-surfaces* and *s-planes*.

1. *s-surfaces* are discrete, visible, more or less continuous surfaces exemplified by structures such as bedding foliation, strain-slip cleavage, segregation banding, and so on.

2. *s-planes* are defined statistically by preferred orientation of one or more constituent minerals. Thus, in the rock from Anglesey which forms the subject of this paper, sharply crystallized flakes of mica tend to be oriented with {001} inclined at a statistically constant angle to the foliation, but show no tendency to be positioned in discrete layers. This plane of preferred orientation of mica although not megascopically visible is an *s-plane* of the fabric.

In general, plastic deformation as defined above favors development of *s-planes*, whereas discontinuous deformation favors appearance or accentuation of *s-surfaces*. In rocks which have suffered flow, the degree of arrangement into surfaces of elements such as mica flakes or grains of quartz with a preferred orientation is a guide to the nature of the deformation. If deformation is continuous, that is, if each grain behaves as a deforming unit regardless of the behavior of the fabric as a whole, then no inhomogeneities (*s-surfaces*) are induced by the movements. On the other hand, if movement is not continuous on the scale considered, then inhomogeneities appear transgressing the whole fabric. Such slip surfaces can be on all scales, from microscopic *s-surfaces* separating layers of the thickness of a single grain or group of grains, to great movement horizons penetrating the largest of rock bodies.

Affine and non-affine deformation by slip.—A monoclinic deformation involving penetrative slip upon one plane is said to be affine if straight lines and planar surfaces within the deformed body before deformation remain straight lines and planar surfaces, respectively, after the deformation. A sphere becomes a triaxial ellipsoid with the mean axis (the axis of slip) as an axis of no change.³ If, on the other hand, what were straight lines and planar surfaces before deformation, respectively become curved lines (lying in one plane) and curved surfaces after the deformation, then slip is said to be non-affine (Knopf and Ingerson, 1938, p. 75-77; Turner, 1948, p. 164-166). Both affine and non-affine deformation by slip are movements with monoclinic symmetry. Non-affine slip is probably more important than affine slip in the evolution of rock fabrics.

External and internal rotation.—In one type of non-affine deformation there is flexure of the slip plane giving flexural slip folding so that there is

³ In rocks this axis is not always an axis of no change. It is commonly an axis of elongation or axial flow (Weiss, 1954, p. 76), and under some conditions of deformation it may be an axis of shortening. But so long as there is no laminar slip along this axis, that is, so long as the symmetry of the deformation remains monoclinic, the deformation remains plane and its geometry is essentially unchanged.

an *external rotation* of one part of the slip plane with respect to another, and of both with respect to coordinates external to the deformed body (Turner, Griggs, and Heard, 1954, p. 898). The deformation remains plane during external rotation; and the axis of external rotation of all elements of the fabric is normal to the deformation plane.

During plane deformation by slip, inactive pre-existing planes (or surfaces) and lines (or lineations) in the fabric undergo *internal rotation*; that is, they are rotated through the fabric by componental movement, with reference to coordinates within the deformed body, in a manner and amount decided by their initial orientation and the degree of deformation. The geometrical principles underlying the internal rotation of one plane by gliding on another have been used by Turner, Griggs, and Heard (1954) in detailed analyses of structures produced in single crystals of calcite by experimental deformation. The axis of internal rotation of one plane by slip upon another is given by the line of intersection of the two planes, regardless of the direction of slip (Borg and Turner, 1953, p. 1348, fig. 3).

Surfaces undergoing internal rotation in rocks may contain one or more lineations. It is important therefore to determine also the axis of internal

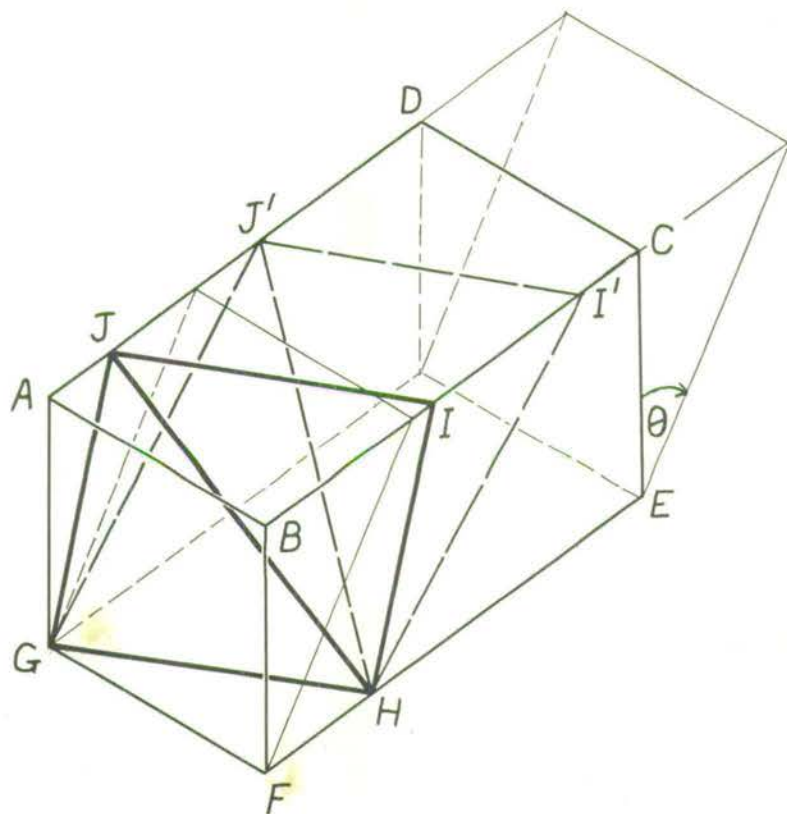


Fig. 1. Geometry of internal rotation of a plane $GHIJ$ and a line HJ by affine slip upon the plane $ABCD$.

rotation of a line relative to that of a plane which contains it. In figure 1 a rectangular prism $ABCDEFGH$ contains a randomly oriented plane $GHIJ$, which in turn contains a line HJ . The prism is deformed by affine slip in direction AD on a plane $ADCB$, the angle of shear being Θ . The plane $GHIJ$ is internally rotated about the axis GH to the position $GHI'J'$, and the line HJ is internally rotated to HJ' . No matter how great the amount of deformation, J' will always lie on AD (the direction of slip), and HJ' will be internally rotated so that it always lies in a unique plane containing the direction of slip. The axis of internal rotation of any line is thus the normal to the plane containing the line and the direction of slip.

B-axes.—There is still, in structural geology, some confusion surrounding the recognition and significance of fabric axes in general and of *B*-axes in particular. It is beyond the scope of this work to trace the evolution of the concept of a *B*-axis; but it is necessary for what follows to define this axis for fabrics with monoclinic symmetry. For the moment we shall not consider *B*-axes in fabrics with either orthorhombic symmetry or triclinic symmetry resulting from the effects of one non-planar deformation.

One purpose of fabric axes is to facilitate description of rock fabrics in a fashion similar to that in which crystallographic axes are used in descriptions of crystals. This purpose may be termed *geometrical*, or, more properly, "*symmetrological*" (*symmetrologisch*; Sander, 1948, p. 132). There is, however, another and more important purpose in defining fabric axes, and that is to describe the movements responsible for the fabric in its present form. In this sense the axes are *kinematic*. It has been necessary, therefore, to define two distinct systems of axes which for ideal rock fabrics are identical. Each system of three orthogonal axes, a , b , and c , can be defined in terms of monoclinic symmetry—the first in terms of monoclinic fabric, the second in terms of monoclinic movement.

1. In the symmetrological system ab is the principal fabric plane. This is the most prominent surface in the fabric, that is, the foliation. The symmetry plane (which, since the symmetry is monoclinic, must be normal to ab) is ac ; and the normal to the plane of symmetry is b . In many deformed rocks ab is folded with b as fold axis. Since b is therefore a direction of maximum continuity in the fabric (as well as the axis of symmetry), it is designated *B*.

2. The kinematic axes are defined for rotational strain involving slip upon one s -plane. The slip plane is ab , the deformation plane is ac , and the normal to the plane of deformation is b . The direction of slip is a . Deformation is commonly by flexural slip of ab ; and b , as the axis of external rotation is again a direction of maximum continuity, designated *B*.

The relationships of these axes are summarized in table 1.⁴

The most fundamental principle of structural petrology—that upon which the kinematic analysis of fabrics is based—states that the symmetry of a deformed fabric preserves the symmetry of the movements which have produced

⁴ The two systems of axes as here defined have one fundamental difference. The symmetrological axes are *descriptive* in that they are applied directly to visible structures, whereas the kinematic axes are *genetic*, applying to the movements which have produced the structures.

TABLE 1

Axis	"Symmetrological" (descriptive)	Kinematic (genetic)
b	Normal to plane of symmetry (ac).	Normal to plane of deformation (ac).
$B=b$	Axis of flexural slip folds of ab . Axis of symmetry.	Axis of flexural slip movements. Axis of external rotation.
a	Normal to B in the foliation (ab).	Normal to B in the slip plane = direction of slip.
c	Normal to foliation (ab).	Normal to slip plane (ab).

that fabric (Sander, 1948, p. 81-83; Griggs, Turner et al., 1951, p. 905). For any rock deformed by slip or flexural slip upon a single foliation, the symmetry plane of the fabric is the deformation plane of the movements which have produced the fabric, and the symmetrological and kinematic axes are the same. This relationship, which is the basis of Sander's methods of fabric analysis, admits of no exception so long as the symmetry of the fabric is truly monoclinic.

Modification of pre-deformational s -surface and s -planes.—Monoclinic movements will give rise to monoclinic ~~movements~~ *fabrics* under three conditions only:

1. If the deformed fabric was statistically isotropic before deformation.
2. If the deformation was sufficiently prolonged or intense to remove by transposition all traces of structures in the original fabric.
3. If structures inherent in the fabric before deformation agreed in symmetry with the deforming movements.

Under all three conditions the B -axes defined symmetrologically coincide with those defined in terms of movement.

Conditions 1 and 2 do not concern us. The first is a special case of limited importance; and the second gives rise to fabrics the full structural history of which cannot be determined by fabric analysis. Much more commonly a monoclinic deformation acts upon an initially anisotropic fabric in which there is a single set of s -surfaces that may be designated S ; for example, the bedding of a sediment, the flow banding of a rhyolite, or the foliation of a schist. Three cases may be recognized:

(a) S is planar and normal to the deformation plane. This condition is generally statistically fulfilled, at least in the early stages of deformation, during the primary deformation of horizontally bedded sediments and sedimentary rocks by slip on and flexural slip folding of the bedding in response to tangential stresses in the Earth's crust. The initially horizontal bedding is folded by movements with a vertical deformation plane; and the horizontal fold axis can be demonstrated on symmetrological grounds to parallel the kinematic B -axis. Condition 3 (above) is fulfilled, and the resultant fabric is monoclinic. But this is a special case reflecting special conditions of deformation.

(b) S is already folded, but the fold axis is normal to the deformation plane of the subsequent movements. Here too the resultant fabric is monoclinic (condition 3).

(c) The general case is that in which the deformation plane intersects S (whether this is planar or already folded generally depends on the scale of the field considered) at angles other than 90° . The foliation is generally unsuitably oriented to act as the slip plane of the deformation, and, under conditions of solid flow, a plane of affine or non-affine slip—again depending on the scale of the field considered—intersects and internally rotates S about axes which vary in orientation with the variation in the initial attitude of S . If this slip plane does not develop as a visible set of surfaces, then S remains the most conspicuous set of s -surfaces in the fabric. The symmetry of the fabric is triclinic.

Significance of triclinic symmetry.—It is normal procedure in fabric analysis (on all scales) to select the foliation of a deformed rock as the ab -plane and the main lineation or fold axis as the B -axis (Knopf and Ingerson, 1938, p. 213; Turner, 1948, p. 177; Fairbairn, 1949, p. 6). Triclinic fabrics (other than those produced by proved triclinic strain) are generally interpreted in terms of two or more B -axes lying in the foliation. It has been stressed by Sander that this is a tentative identification to await full analysis of the fabric for confirmation; nevertheless, it has given rise to fundamental misconceptions of the geometry of tectonites as illustrated by Fairbairn's (1949, p. 6) statement: "If foliation is developed, as is commonly the case, b lies in the foliation surface." This statement holds without exception *only for fabrics with undoubted monoclinic symmetry on all scales*. The fabrics of most tectonites, when all structural elements are taken into consideration, have slightly triclinic symmetry. By selecting a planar foliation in these rocks as ab we are limiting the orientation of B to a single plane, without proper regard for the symmetry of the fabric. Likewise, the unqualified equation of B with the fold axis in folded rocks with any degree of triclinic symmetry, however small, can be an oversimplification of the true geometrical facts. Folds with triclinic symmetry can be associated with monoclinic movements in at least two ways:

1. Folds of a set of s -surfaces (S_1) inherent in the fabric before deformation on an intersecting s -plane (S_2) can survive a certain degree of internal rotation, and retain their identity as folds, although not their orientation or direct kinematic significance.

2. Slip or flow folds of a set of inherent planar s -surfaces (S_1) can form by internal rotation in response to non-affine slip on an obliquely intersecting s -plane (S_2).

Although both of the above types of fold can have well-defined fold axes, these axes are not as a general rule parallel to the kinematic B -axes of the monoclinic deforming movements. The fabrics concerned show, on all scales, a tendency toward triclinic symmetry which expresses an equivalent tendency for the kinematic B -axis to depart from parallelism with the foliation. Even fabrics in which on a large scale there is statistical monoclinic symmetry can possess, on a small scale, some degree of triclinic symmetry. A

genuinely monoclinic fabric, on the scale of one hand specimen, is very rare. In most tectonites a combination of lineations, folds, *s*-planes, *s*-surfaces and patterns of preferred orientation of minerals collectively defines triclinic symmetry of fabric.

To summarize; as a general rule, layered rocks that undergo monoclinic deformation by solid flow which does not agree exactly in symmetry with structures inherent in the predeformational fabric develop fabrics having overall triclinic symmetry. In such fabrics the kinematic *B*-axis commonly does not lie in the foliation, and its orientation must be determined by geometrical analysis of all orientation data. Common procedure of accepting foliation as *ab* and explaining triclinic symmetry in terms of superposed symmetrological *B*-axes, both lying in the foliation, leaves the way open for fundamental errors in interpretation of structural data. None of the *B*-axes determined symmetrologically, in effect, may be parallel to the kinematic *B*-axis. The tectonite now to be described will serve to illustrate these points.

THE TRICLINIC TECTONITE FROM ANGLESEY

Petrofabric analysis.—The rock is a dark brown quartz-albite-mica schist with a well-marked foliation defined by layers alternately richer in muscovite and deep brown biotite. The grain size is small (average mean grain dimension about 0.2 mm) and approximately uniform. In thin section the rock consists of a mosaic of equidimensional quartz grains, enclosing scattered non-twinned porphyroblasts of albite full of minute inclusions, small undeformed flakes of muscovite and biotite and small rounded granules of clinozoisite.

In the foliation (S_1) two lineations can be seen:

1. A very fine regular parallel ribbing (L_1).
2. A weaker more imperfectly developed lineation (L_2) inclined at 32° to L_1 .

From several thin sections the preferred orientation of the poles of {001}-planes in muscovite and biotite and the [0001]-axes in quartz were measured and plotted on the lower hemisphere of an equal area projection. The preferred orientations of these directions are surprisingly homogeneous throughout the hand specimen, and the data for mica and quartz were rotated into the plane normal to L_1 and combined to give two synoptic diagrams (figs. 2a and 2b, respectively).

The poles of {001}-planes of the mica flakes are arranged in a strong maximum, actually a double maximum (fig. 2a), inclined to the pole of S_1 , and spreading into a perfectly developed girdle about L_1 . The plane (S_2), statistically defined by the weighted maximum of {001}-poles, intersects S_1 in L_1 . The quartz diagram (fig. 2b) shows a preferred orientation of [0001]-axes in a broad girdle asymmetrically oriented with respect to L_1 and the mica girdle. An area of maximal concentration of axes is situated close to, but not in S_1 . The axis of the girdle similarly is close to, but does not coincide with, L_2 . Although no A.V.A. (Ramsauer, 1941; Weiss, 1954, p. 63-70) has been made, investigation with a gypsum-plate suggests that the preferred orientation of quartz is essentially homogeneous, that is, unrelated to slip surfaces in the fabric. The crystallization of quartz and mica is postkinematic.

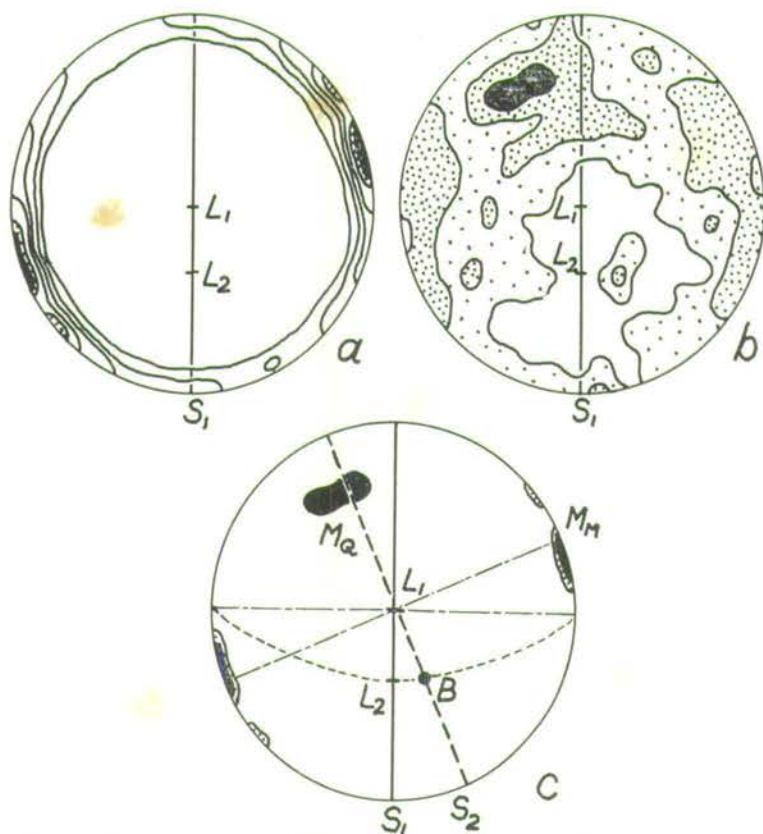


Fig. 2. Preferred orientation data from a triclinc tectonite from Anglesey.

- a. 761 {001}-poles of muscovite and biotite. Contours: 2.4-6.8-10-12% per 1% area.
 b. 600 [0001]-axes of quartz. Contours: 1-2-3% per 1% area.
 c. Synoptic diagram to show the geometry of the fabric.

S_1 —foliation.

S_2 —s-plane statistically defined by the preferred orientation of mica.

L_1, L_2 —lineation lying in the foliation.

M_q —quartz maximum.

M_m —mica maximum.

B —axis of quartz girdle.

L_1 is horizontal, trending northeast—southwest: it is viewed in the southwest sense.
 S_1 dips 76° to the northwest.

Interpretation of fabric data.—The symmetry of the fabric is obviously triclinc. Two alternative interpretations of the data are given below. The first is consistent with normal procedure in fabric analysis as outlined in various reference books (Knopf and Ingerson, 1938, p. 213; Turner, 1948, p. 217; Fairbairn, 1949, p. 5-6). The second is based on the geometrical considerations outlined above and is that preferred by the present writer.

1. According to normal procedure, S_1 would be selected as ab , L_1 as one symmetrolgical B -axis, and L_2 as another. L_1 would be interpreted as

the earlier axis associated with the more intense movements responsible for the preferred orientation of mica, and L_2 would be attributed to later much weaker movements sufficiently strong only to reorient the quartz and leave a faint lineation. Each symmetrological B -axis would be considered to coincide with a corresponding kinematic B -axis, and the tectonite would be interpreted as a $B \wedge B'$ -tectonite in terms of two monoclinic deformations.

2. A completely different interpretation of these same fabric data, based on geometrical analysis, is more satisfactory in that it explains several features of the quartz fabric that otherwise appear merely coincidental. First, the girdle of $[0001]$ -axes is more nearly normal to B (fig. 2c) than to L_2 (fig. 2b). Second, as seen in figure 2c, B lies in the statistically defined plane S_2 . Third, the maximum concentration of $[0001]$ -axes also lies in S_2 and is roughly normal to B . All these features can be correlated with deformation by slip normal to B in a slip plane S_2 , in which case the main quartz axis maximum would be equivalent kinematically to the familiar Maximum I of Sander's synoptic diagram (Turner, 1948, p. 260). Moreover, S_2 intersects S_1 in L_1 , the axis of the mica girdle, and it is the plane of preferred orientation of $\{001\}$ -planes of mica. In other words, the movements upon S_2 are responsible for the preferred orientation of both mica and quartz. Non-coincidence of mica and quartz girdles can be explained by assuming that mica in the initial fabric was oriented parallel to S_1 and that S_1 was internally rotated during the subsequent deformation by slip on S_2 normal to B . We know that this slip was affine on the scale of one hand specimen; otherwise S_1 would be slip folded about L_1 as fold axis. The mica flakes rotated from S_1 toward S_2 have assumed a pattern of preferred orientation in a girdle whose axis is L_1 —the intersection of S_1 and S_2 —although *this axis is not the kinematic B -axis of the deforming movements*. The only kinematic B -axis recognizable in the fabric is B , the axis of the quartz girdle, which does not lie in the foliation (S_1). The lineation L_2 is the projection or trace on S_1 of a linear structure (most probably an elongation of quartz grains) lying in S_2 parallel to B . The geometry of this trace is shown in figure 2c—the plane normal to S_1 containing B intersects S_1 in L_2 (Clark and McIntyre, 1951, p. 757).

The evolutionary history of the fabric may be summarized as follows: a rock with either a sedimentary or metamorphic layering (S_1) was deformed by continuous plane deformation involving affine slip upon a mechanically induced slip plane (S_2). The deformation was sufficiently homogeneous to prevent the development of discrete microscopically visible s -surfaces of slip. The kinematic B -axis lay not in the initial foliation (S_1) but in the mechanically induced plane of slip (S_2). The mica flakes initially lying in the foliation were rotated about L_1 toward the slip plane S_2 . The preferred orientation of quartz suggests that there was an incipient alignment of $[0001]$ -axes in the slip direction (the kinematic a -axis), accompanied, perhaps, by fracture and granulation of the previously existing quartz grains. Such a cataclastic history of the quartz would be concealed by the complete postkinematic crystallization which has affected the fabric, although the preferred orientation would be preserved. The mica flakes may have recrystallized more nearly parallel to

the actual plane of slip than they were brought by rotation during the deformation.

The quartz and mica girdles, although not coaxial, have thus been produced during a single phase of movement. The kinematic B -axis of this movement is most clearly defined by the preferred orientation of quartz; whereas the slip plane S_2 is defined by the preferred orientation of mica and to a lesser extent quartz. The megascopic fabric considered alone gives no guide to the orientation and significance of the kinematic B -axis. Neither of the two lineations visible in the foliation is parallel to B , although movements normal to it have produced them both.

GENERAL CONCLUSIONS

1. Not all visible lineations in tectonites represent B - or a -axes. Nor are all triclinic fabrics produced by two superposed non-coaxial deformations. On the contrary, many triclinic fabrics are products of monoclinic deformations acting upon initially layered fabrics which do not agree in symmetry with the deforming movements. Lineations in these fabrics commonly parallel the intersection of the initial lamination with the slip plane (axis of internal rotation), and do not have constant orientation although the kinematic B -axis lying in the slip plane does. This concept may be stated in a different manner. It is commonly assumed that the B -axis of a deformed fabric lies in the foliation. This may be a general rule for rocks deformed by proved slip upon the foliation; but it cannot apply to many rocks which have suffered solid flow during plane deformations in which the B -axis transects structures inherent in the initial fabric.

2. For this reason current procedure of selecting tentatively the most prominent surface in the rock as ab , and the most prominent lineation as B , is liable to give rise to a basically two dimensional interpretation of the orientation data, governed by the foliation. A more descriptive primary nomenclature is advised: S_1 , S_2 and so on for surfaces and planes, L_1 , L_2 and so on for lineations, and F_1 , F_2 and so on for the axes of folds. Complete fabric analysis, on all scales, of selected specimens and areas should follow, with particular attention paid to geometry and symmetry of fabric.

3. Microscopic fabric analysis is of great importance in structural geology as a means of evaluating the significance of megascopically visible lineations, folds and so on, and of demonstrating the existence of statistically defined s -planes. The constant orientation of quartz girdles, regardless of the megascopic fabric, recorded in Bergsdalen by Kvale and in Anglesey by the writer, suggests the presence of a constantly oriented kinematic B -axis in these two areas. The importance of mica as a guide to the kinematics of a fabric lies in its tendency to become oriented with $\{001\}$ lying in planes and surfaces. The $\{001\}$ -poles of mica define not only axes of external rotation of surfaces but also axes of internal rotation which are not always B -axes. The non-equidimensional habit of mica means that its initial orientation will exert an influence upon its final orientation during movement in a fabric. This property it shares with all surfaces in rocks, together with which it may be classed as a *dependent* fabric element. Quartz, on the other hand, with no tabular habit,

is more free from influence of an initial orientation; and it tends to reflect more nearly in its orientation the geometry and symmetry of the movements by which the orientation is produced. Quartz may be classed as an *independent* fabric element.

4. Non-coaxial quartz and mica girdles have hitherto been considered evidence in favor of the view that quartz can acquire a preferred orientation, by some unknown mechanism, without appreciable penetrative movement in a fabric. Therefore, fabrics showing such girdles should be subjected to the most thorough geometrical and kinematic analysis in order to confirm that the differently oriented girdles do not merely record different axes of rotation of the same movements.

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I. 6. The Significance of Symmetry in Tectonites.

THE SIGNIFICANCE OF SYMMETRY IN TECTONITES

by

L.E. WEISS

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ABSTRACT

The symmetry of the fabrics of some rocks deformed by flow appears to be different from the symmetry of strain. It is suggested that symmetry of fabric agrees with symmetry of strain, without exception, only where all the structural elements used to determine symmetry of fabric have participated in a mechanically active fashion in the strain of the fabric. Elements which have participated passively in strain can define a symmetry of fabric lower than symmetry of strain. The terms primary and secondary symmetry are suggested to denote the two kinds of symmetry.

It is shown that primary and secondary symmetry can occur theoretically on all scales in deformed layered rocks; and that, in general, primary symmetry is to be correlated with S - active flow and secondary symmetry with S - passive flow. The significance/

significance of fabric axes in fabrics with monoclinic, triclinic and orthorhombic symmetry is discussed. Lines of kinematic and structural evolution of a horizontally layered body in response to biaxial and triaxial strain are suggested. It is shown that, along these lines, symmetry of fabric can change from primary to secondary as deformation progresses. It is shown also that both primary and secondary symmetry can arise by superposition of two genetically unrelated strains.

1. INTRODUCTION

One of the most important concepts in structural analysis of rocks deformed by flow is the concept of symmetry. It is generally accepted, following Sander, that the symmetry of the fabric of a tectonite expresses the symmetry of the penetrative movements which have occurred in the fabric as a result of deformation: (see, for instance, Knopf and Ingerson, 1938, p. 42). Within recent years the validity of this view/

view has been questioned by structural geologists, once by Anderson (1948, p. 121) and twice by Kvale (1946 and 47, p. 194, and 1953, p. 52 and 53). Also, the writer (Weiss, 1955) has described a tectonite from Anglesey with triclinic symmetry of fabric attributed to the effects of a monoclinic movement. It must be concluded that recognition of symmetry of movement on the basis of symmetry of fabric is not always straightforward. It is the purpose of this paper to examine the significance of the different kinds of symmetry found in tectonites, in order to determine the factors which limit the extrapolation from symmetry of fabric to symmetry of strain.

In order to examine the significance of symmetry in tectonites it is necessary to consider some geometrical features of flow in rocks. This is done schematically by reducing the complex processes of flow and the complex relationships of stress and strain in rocks to their simplest terms. To those geologists whom he has offended by this oversimplification the/

the writer offers his apologies. The simplifications are necessary before *geometry* and symmetry of flow can be discussed, in any but the broadest terms.

The writer must take full responsibility for most of the views expressed in this paper. Some attempt has been made to tie these views into a philosophical framework similar to that of the great Austrian structural geologist Bruno Sander; but if because of difficulties of translation, the views of Professor Sander are in any way misrepresented then the writer alone is responsible.

2. DEFORMATIONAL FLOW OF ROCKS

Many strongly deformed rocks at present in a rigid and brittle state show evidence of having possessed at one or more periods in their structural history a mobility similar to that of a viscous fluid or a plastically deforming solid. In order to ~~denote~~ the process whereby a rock is deformed continuously in space without loss of cohesion the descriptive term flow is used. The mechanisms/

mechanisms of deformational flow in rocks are varied and imperfectly understood. The most complete accounts of modern views upon phenomena of flow in rocks are to be found in Knopf and Ingerson (1938, pp. 86-191), Turner (1948, pp. 225-237) and Fairbairn (1949, pp. 77-115 and pp. 199-214).

It is accepted generally that at least four mechanisms are important in rock flow, as follows:

1. Plastic flow: that is, intracrystalline translation and twin-gliding. This is demonstrably of great importance as a mechanism of flow in marbles and dolomite rock (see, respectively, Griggs, Turner, Borg and Sosoka, 1953 and Turner, Griggs, Heard and Weiss, 1954), and it is probably of some importance in most rocks.

2. Cataclasis: extreme deformation of pure quartzite sometimes takes the form of what may be termed cataclastic flow, although this phenomenon must include mechanisms, such as recrystallization, other than cataclasis. Flow proceeds by a process of comminution of large grains by fracture into minute granules.

3./

3. Intergranular slip: cataclastic flow and intragranular plastic flow in polycrystalline aggregates cannot proceed unless some degree of differential movement of grains by slip ^{at} as grain boundaries is possible.

4. Recrystallization: so-called pseudoviscous flow (Fairbairn, 1949, pp. 86, 87) is thought to be largely a result of recrystallization involving the solution and precipitation of ions respectively in stressed and unstressed portions of grains, perhaps according to Riecke's Principle. The presence of a fluid interstitial phase may be either desirable or imperative for this kind of flow to take place. Unlike other mechanisms, this mechanism, in itself, is unlikely to produce a marked change in preferred orientation of grains unless grains are dissolved selectively and completely according to the orientation of their crystal lattices. Great changes in the shape of grains probably arise in this fashion.

These four mechanisms fall into the category called/

called by Sander (1950, p 2, 3) componental movements (Teilbewegung). The observed strain of a fabric by deformation is a result of the integration of these componental movements in a fashion which, on most scales, may be considered spatially continuous. A fabric strained by flow preserves in the orientation and disposition of its components a record of the nature of the movements which have affected them. A fabric which bears a structural imprint, on all scales, left by penetrative movement of this kind is termed a tectonite, and it is with such rocks that this paper is concerned.

The fabrics of tectonites are products of evolutionary processes. The driving force behind the evolution is the dynamic environment of the rock and its modus operandi is componental (penetrative) movement. Modern methods of structural analysis, in particular those developed and applied by Bruno Sander and his coworkers in Innsbruck, depend upon the intimate relation which, in the fabric of a tectonite, exists between the geometry and symmetry of its structural components and the/

the geometry and symmetry of the movements which have been responsible for their formation and arrangement. In examining the orientation and disposition of microscopic structural elements, a structural geologist is examining the components involved in componental movement, and it is best to begin an enquiry into the significance of symmetry of fabrics by considering structural elements on a microscopic scale; but first of all it is necessary to consider two interrelated concepts which enter into all structural investigations in rocks.

3. SCALE AND HOMOGENEITY

Although three "absolute" scales (microscopic, macroscopic and megascopic) are generally recognized in structural analysis, there is no fundamental difference to be drawn between them with regard to possible degrees of structural homogeneity. A strongly deformed mineral grain with twin - and translation-gliding can be/

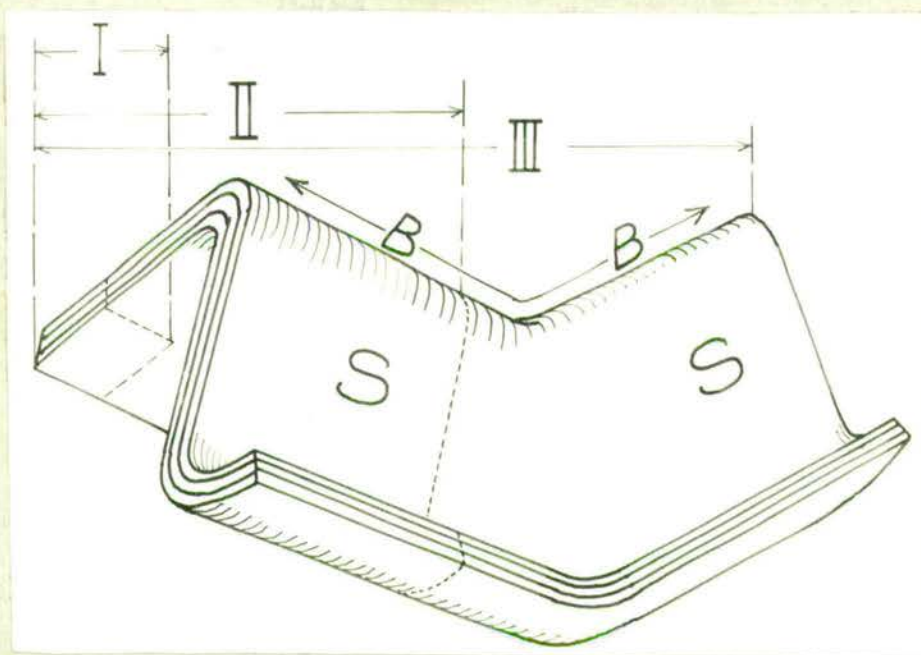


Figure 1. Fields of homogeneity with respect to S and B.

can be as inhomogeneous on its own scale with respect to its own structural elements as can a mountain. When discussing homogeneity in structural analysis it is necessary first, to distinguish between homogeneity of fabric and homogeneity of deformation, and second, to determine relative homogeneity on different scales with respect to specific structural elements. As an example of the use in structural analysis of homogeneity of fabrics, the body shown in figure 1 is considered. The absolute scale is immaterial. A set of parallel surfaces (S) is cylindroidally folded about an axis (B) and the elongate structure so formed is bent. For this example it is assumed that the penetrative structures produced by the bending are confined to the immediate vicinity of the bend. Fields on various scales (I, II and III in figure 1) have the following degrees of homogeneity with respect to the orientation of S and B;

field I is homogeneous with respect to both S and B
field/

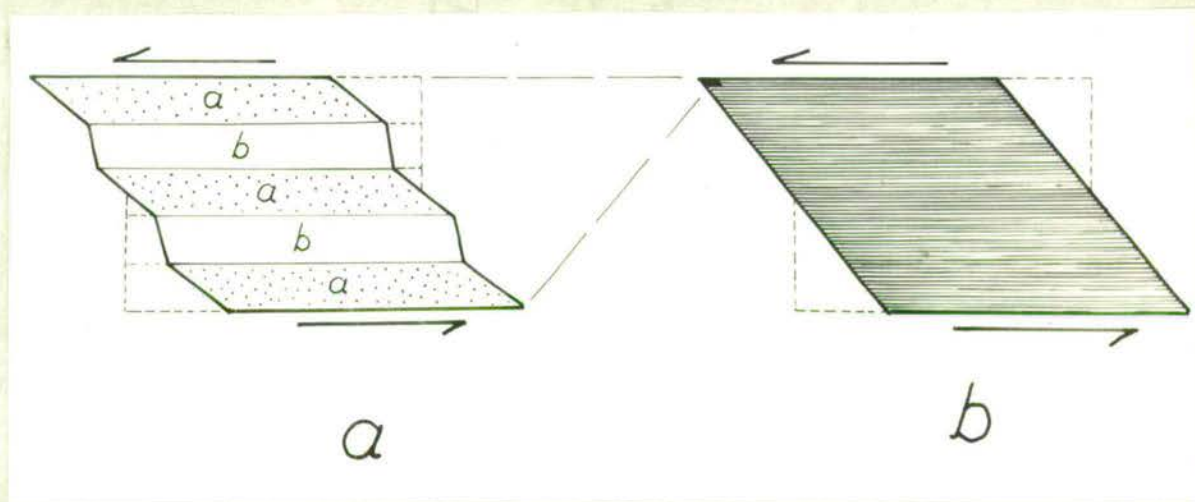


Figure 2. Change of statistical homogeneity of deformation with change of scale.

field II is inhomogeneous with respect to S but homogeneous with respect to B;

field III is inhomogeneous with respect to both S and B.

If the cylindroidal folding of S is by flexural slip (S is the surface of slip), the degree of deformation in individual layers parallel to S of finite thickness can vary. Such a variation means that, although it is homogeneous with respect to the orientation of S, field I is not necessarily homogeneous with respect to those elements of the fabric which reflect the amount of penetrative movement distributed through any one layer of finite thickness. For instance, if slip on S is concentrated in certain layers (a in figure 2a) which separate layers in which deformation is less pronounced (b in figure 2a), then the fabric in the layers a and b must be correspondingly inhomogeneous in certain respects. Plainly they are homogeneous with respect to the orientation of S; but if layers a are, say, pure quartz and layers b are, say quartz plus feldspar/

feldspar, then it is probable that the degree of preferred orientation of quartz in layers a and b is different; that is, the field is inhomogeneous with respect to the degree of preferred orientation of quartz. But, because movements in layers a and b differ in amount only and not in kind, the symmetry (see below) of the preferred orientation of quartz probably is homogeneous throughout. Alternatively, field I can be structurally homogeneous in all respect down to the granular scale. Many marbles and other monomineralic or mineralogically uniform rocks have such homogeneity.

Whether or not inhomogeneities of the kind just described are significant in structural analysis depends largely upon the size of the field considered relative to the scale of the inhomogeneities. On the scale pictured diagrammatically in figure 2a, slip on S is non-affine and the field is inhomogeneous; but if the field is part of a very much larger field with the same kind of small scale inhomogeneity, then the fabric can be statistically/

statistically homogeneous on the larger scale (figure 2b). This example is analogous to the affine deformation by slip of a thick pack of very thin cards. There is no slip in the cards themselves so that a straight line inscribed upon the side of the card pack before deformation becomes, after deformation, "stepped" on the scale of a few cards. On this scale the fabric and movement are inhomogeneous, whereas on the scale of the whole pack, fabrics and movement are statistically homogeneous. A similar state of affairs exists in some deformed rocks such as the Yule marble deformed "homogeneously" by experiment (Griggs and Miller, 1951, pp. 857-862), although in this instance deformation is not by slip on a single set of planar surfaces. In Yule marble each grain behaves in a manner decided by its own crystallographic orientation and the external stresses; but because the grains are small relative to the whole specimen the change in shape of the specimen is similar to what it would be for a homogeneous deformation.

There is thus no hard and fast correlation between/

between scale and homogeneity unless the degree of homogeneity is established with respect to definite structural elements; and, even so, statistical homogeneity on a large scale with respect to a particular structural element sometimes can be established in rocks in which on a small scale the fabric is inhomogeneous with respect to the same structural element. This is not true only on scales involving study of grain orientation such as the example cited. Differential behaviour of layers and bodies on any scale can give rise to the same kind of statistical homogeneity. For instance, if field II in figure 1 is part of a much larger field folded in the same manner (figure 3), then this large field may be considered to be statistically homogeneous with respect to the orientation of \underline{S} , which is statistically planar.

Because of the infinite variety of possible inter-relations of scale and degrees of homogeneity, no absolute scale has a corresponding absolute homogeneity. For this reason there is no fundamental difference between structural/

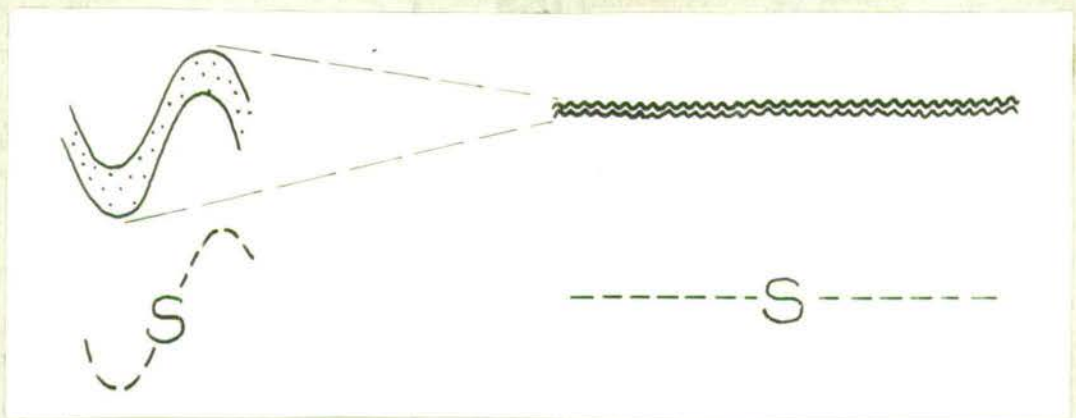


Figure 3. Flexural slip folding as a statistically homogeneous deformation on a large scale.

structural analysis on the three absolute scales. A diagram showing preferred orientation of grains prepared from a single thin section can show a degree of structural homogeneity analogous to that of a diagram showing preferred orientation of macroscopic structural elements prepared from a large body of rock. This fact is important because there is a tendency, especially among British geologists, to look upon structural analysis on the microscopic scale as something fundamentally different from structural analysis on other scales. For this reason microscopic structural analysis is rarely used in Britain, and, mostly improperly when it is.

4. THE PRINCIPLE OF SYMMETRY

The use of symmetry in study of nature and effects of deformation probably is peculiar to structural geologists. Other workers dealing with deformation tend to use more precise methods of analysis of fields of stress and strain. But the concept of symmetry is invaluable in practical evaluation of the significance/

significance of orientation diagrams produced by the graphical methods of statistical analysis used in tectonics. With reference to the use of symmetry in structural analysis, the following facts are important:

1. Symmetry is defined statistically in the same fashion as homogeneity. Although the systems used to denote symmetry in structural analysis are the same as those used to denote the symmetry of crystal lattices, they possess none of the precision of the crystallographic systems.

2. In structural analysis, symmetry can refer to fabric, movement (strain or distortion) and stress.

3. Symmetry must be considered together with scale. As statistical homogeneity can vary with scale in a single field of deformation, so can statistical symmetry.

Symmetry in structural analysis is defined in terms of planes of mirror symmetry. In naturally deformed rocks only three systems need be considered; a fourth kind, axial symmetry (the symmetry of a cylinder) probably occurs rarely or not at all in tectonites. The three/

three kinds of symmetry are:

1. Orthorhombic symmetry - three mutually perpendicular planes of symmetry
2. Monoclinic symmetry - one plane of symmetry
3. Triclinic symmetry - no plane of symmetry.

The foregoing remarks are introductory to the principle upon which the edifice of structural analysis can be said most heavily to rest. This principle may be called the principle of symmetry, or, as E. M. Anderson (1948, p. 122) has called it, "the argument from symmetry". It is simply this, that the symmetry (the internal statistical symmetry) of the fabric of a tectonite reflects the symmetry of the movements which have affected it.

The principle of symmetry covers only the relation between symmetry of movement and symmetry of fabric. A system of external stresses also can be expressed in terms of symmetry, but only for homogeneous deformation of a homogeneous body can analogous principle of symmetry be outlined to cover the relation between symmetry/

symmetry of stress and symmetry of movement. Likewise, the principle of symmetry covering the relation between movement and fabric has to be modified to explain certain rock fabrics which are apparently exceptions to the principle. Before describing the features of one such fabric, some observations made during the experimental deformation of Yule marble and their bearing on the principle of symmetry are considered. These observations were outlined to the writer in a personal communication from F. J. Turner of the University of California.

The experiments are compressional or tensional deformations with axial symmetry made upon small cylinders of Yule marble in which the preferred orientation of $[0001]$ - axes of calcite is known. The following conditions are thus fixed:

1. The symmetry of loading, which is ideally axial with an axis of symmetry parallel to the load. But where there is eccentricity of load, the symmetry of the load is monoclinic and a shear zone develops.

2./

Erratum, page 119, line 13 and following:

"2. Where load is parallel to the foliation, the two axes of symmetry are mutually perpendicular and the cylinders become elliptical in cross section (orthorhombic symmetry of strain).

3. Where load is inclined, but approximately normal to the foliation, the two axes of symmetry are mutually inclined and the cylinders become elliptical in cross section parallel to a transcurrent shear zone which forms (monoclinic symmetry of strain)".

2. Symmetry of fabric, which is axial with an axis of symmetry normal to the foliation. The pattern of preferred orientation of $[0001]$ - axes of calcite is a single maximum normal to the foliation.

The symmetry of movement is deduced from the geometrical outlines of the cylinder after deformation. With various orientations of the two axes of symmetry (one of stress, the other of fabric) the following results are obtained:

1. Where load is ~~parallel~~ to the foliation, the two axes of symmetry coincide; cylinders remain circular in cross section (axial symmetry of strain). ? perpendicular

2. Where load is parallel to the foliation, the two axes of symmetry are mutually perpendicular and the cylinders become elliptical in cross section parallel to a transcurrent shear zone which forms (monoclinic symmetry of strain).

Several conclusions can be drawn from these results. First, the symmetry of stress equals symmetry of movement only where the symmetry of structural anisotropy present in the fabric before deformation coincides with the symmetry/

symmetry of stress (result 1). Second, where symmetry of stress and symmetry of initial fabric do not coincide the symmetry of movement is a compromise between the two but lower than either (results 2 and 3). The symmetry of stress and the symmetry of fabric in the experiments are both axial, and the lowest symmetry which can arise from a superposition of two axial symmetries is monoclinic. Third, the symmetry of the resultant fabric invariably equals symmetry of strain (results 1, 2 and 3); that is, the principle of symmetry is upheld.

These results are of great importance in that they indicate the effects of structural anisotropy in a fabric on the strain which results from a given pattern of external stress. Further, they provide support for the validity of the principle of symmetry. In the introduction it was pointed out that certain fabrics appear to behave in a fashion contrary to that dictated by the principle of symmetry, and that the principle has been questioned by some structural geologists. In the view of the writer, both Anderson and Kvale have in-substantial/

substantial reasons for questioning the validity of the principle; but the existence of micro-fabrics with symmetry apparently different from symmetry of strain suggests that the principle does have limitations when applied to micro-fabrics. The factors which, in the view of the writer, are responsible for these limitations are now discussed.

5. PRIMARY AND SECONDARY SYMMETRY OF MICROFABRIC

As a preliminary to the discussion which follows it must be stressed that the symmetry of a fabric can be determined only by considering the symmetry of all its penetrative structural elements (foliation and other s- surfaces, folds, lineations, patterns of preferred orientation of mineral grains and so on). Commonly, the symmetry defined by one structural element does not agree with that defined by another; or two elements, each with high symmetry, may combine to define a lower symmetry for the fabric as a whole. Also, when studying symmetry it is imperative to consider scale. In this section/

section concern is with fields on a microscopic scale.

In a recent paper (Weiss, 1955), the writer described a tectonite with triclinic symmetry believed to have been produced by movements with monoclinic symmetry. In other words, the fabric described is one in which the principle of symmetry is invalid. How can this result be reconciled with the results of the experiments on Yule marble in which the principle of symmetry is invariably upheld? The reason for this apparent ^{contradiction} ~~anachronism~~ is as follows; in the experiments on Yule marble the important initial structural anisotropy is a preferred orientation of $[0001]$ -axes of calcite with a concomitant preferred orientation of planes of potential intragranular twin- and translation-gliding of which the deformation must make use. This anisotropy thus is destined to control strain and to play a mechanically active role in deformation. Calcite in Yule marble, therefore, is an active structural component which, during deformation, controls the symmetry of strain that can result from a given system of external stresses/

stresses. The symmetry of the resultant fabric agrees with the symmetry of strain because the only structural component in the fabric (calcite) participates actively in deformation. In this context active behaviour can be defined as intragranular strain.

In the tectonite from Anglesey the symmetry of preferred orientation of quartz is monoclinic. So also is the symmetry of the preferred orientation of mica; but the axes of symmetry of the two are mutually inclined so that the overall symmetry of the fabric is triclinic. It was suggested (Weiss, 1955, p. 235, 236) that these differences in geometry of preferred orientation indicate not a difference in the movements responsible for the two preferred orientations, but a difference in behaviour of the components quartz and mica in a single phase of deformation. This difference in behaviour seems to depend to some extent, upon concentration and mineralogical environment of each component. The fabric of the tectonite is composed mostly of quartz grains with isolated flakes of mica scattered throughout. Statistically, most of the intergranular/

intergranular contacts in the rock are between quartz and quartz, and between quartz and mica; there are few or none between mica and mica. In other words, the "strength" of the fabric, that is, its ability to resist deformation, is decided mainly by a three dimensional structure of quartz with interstitial mica. The term "framework" is suggested to denote a three dimensional arrangement of grains of a single mineral which comprises the structure skeleton of a fabric. In the tectonite from Anglesey, the framework of the fabric is of quartz so that stress is transmitted by this framework and, on deformation, strains appear in it. The mica is interstitial in the framework of quartz and does not constitute a framework because it is statistically always in contact with quartz. Stresses are transmitted to the mica through the framework of quartz so that mica is deformed in an intragranular fashion (for instance, by translation gliding on (001) - planes or by cataclasis) only if mica deforms in this fashion more easily than quartz deforms by intragranular strain; otherwise the mica flakes remain/

remain mechanically passive in a matrix of mechanically active quartz. An analogy is given by small metal discs enclosed in plasticene. Unbalanced stresses which would deform a three dimensional framework of small metal discs where one is in contact with another do not deform the discs where these are embedded in a framework of plasticene. The plasticene is much more easily deformed; and, although the metal discs are moved in an intergranular fashion in response to flow in the plasticene, they do not participate actively in the strain of the body. They retain their initial form after deformation but not their orientation. It is suggested that the behaviour of the mica in the tectonite under discussion was a passive behaviour in a framework of mechanically active quartz. In this way can be explained the differential orientation of the two components in a single phase of deformation.

In Yule marble, deformed experimentally, the framework is of calcite which deforms by intragranular plastic flow and is always active. The strain of a fabric on a large scale is an integration of the strain of mechanically active components and is unaffected by ~~the~~ changes/

changes in the orientation of mechanically passive components. The penetrative movements produced by a given system of external stresses are decided by the behaviour of mechanically active structural components. For instance, a pack of cards squeezed obliquely to the surfaces of the cards by a compression with axial symmetry deforms by slip on the cards. The strain has monoclinic symmetry and so has the resultant "fabric". The axial symmetry of stress is not reflected in the symmetry of strain, which is monoclinic, but the principle of symmetry is upheld because the symmetry of fabric agrees with the symmetry of strain. This is because the framework of cards possesses an internal anisotropy which is mechanically active. Structurally passive markings on the sides of the card pack do not affect the strain of the pack, although, if their symmetry after strain is included in the overall symmetry of fabric, they may modify this symmetry until it no longer agrees with symmetry of strain.

It is suggested that a structural component which behaves actively during deformation can affect the course of/

of deformation, that is, the symmetry of strain resulting from a stress of given symmetry; and it is further suggested that a component which behaves passively during deformation can affect the resultant symmetry of fabric. For this reason it is important, when studying symmetry of fabric and making kinematic and dynamic interpretations, to determine whether a particular component has behaved actively or passively during strain of a fabric. It is impossible here to state criteria for recognition of active behaviour of individual components in deformed rocks because insufficient is known about mechanisms of intragranular strain in most minerals; but some factors are considered which the writer believes to be a starting point for future studies. In a given fabric, it is suggested that whether or not a given component behaves actively or passively depends upon the following factors:

1. The physical conditions governing deformation are certainly important.
2. The intracrystalline properties of the mineral decide/

decide whether it can deform by intragranular plastic or cataclastic flow under any usual conditions of deformation.

3. The concentration of the mineral within a fabric is of great importance. Any mineral which forms a framework in a fabric is usually active mechanically.

4. Whether a particular mineral behaves actively or passively depends upon the nature and concentration of other minerals in the fabric. If the associated minerals are more easily deformed and in greater concentration, a given mineral is more likely to behave passively and vice versa.

5. Active behaviour does not depend only upon the ability to deform mechanically by intragranular strain. Indirect componental movements likewise may produce a behaviour which is essentially active and so ease of recrystallization also is an important factor.

From studies of fabrics of deformed rocks the writer believes that four common rock forming minerals can be arranged in the following order with respect to certain/

certain properties:

1. Feldspar
2. Mica
3. Quartz
4. Calcite

It is suggested, first, that each mineral, under most conditions of deformation, behaves passively in a framework of a mineral lower on the list, and second, that each mineral is active in a framework of a mineral higher on the list. Thus, feldspar is passive in frameworks of mica, quartz or calcite; mica is passive in frameworks of quartz and calcite, and quartz is passive in a framework of calcite. Also, calcite is active in frameworks of quartz, mica or feldspar, quartz is active in frameworks of feldspar. Apart from feldspar, which may be rarely active in deformed rocks, any one of these minerals constituting a framework is always active whether the interstitial grains are active or passive. In figure 4 are shown diagrammatically four fabrics (with postkinematic crystallization) to demonstrate some of the active-/

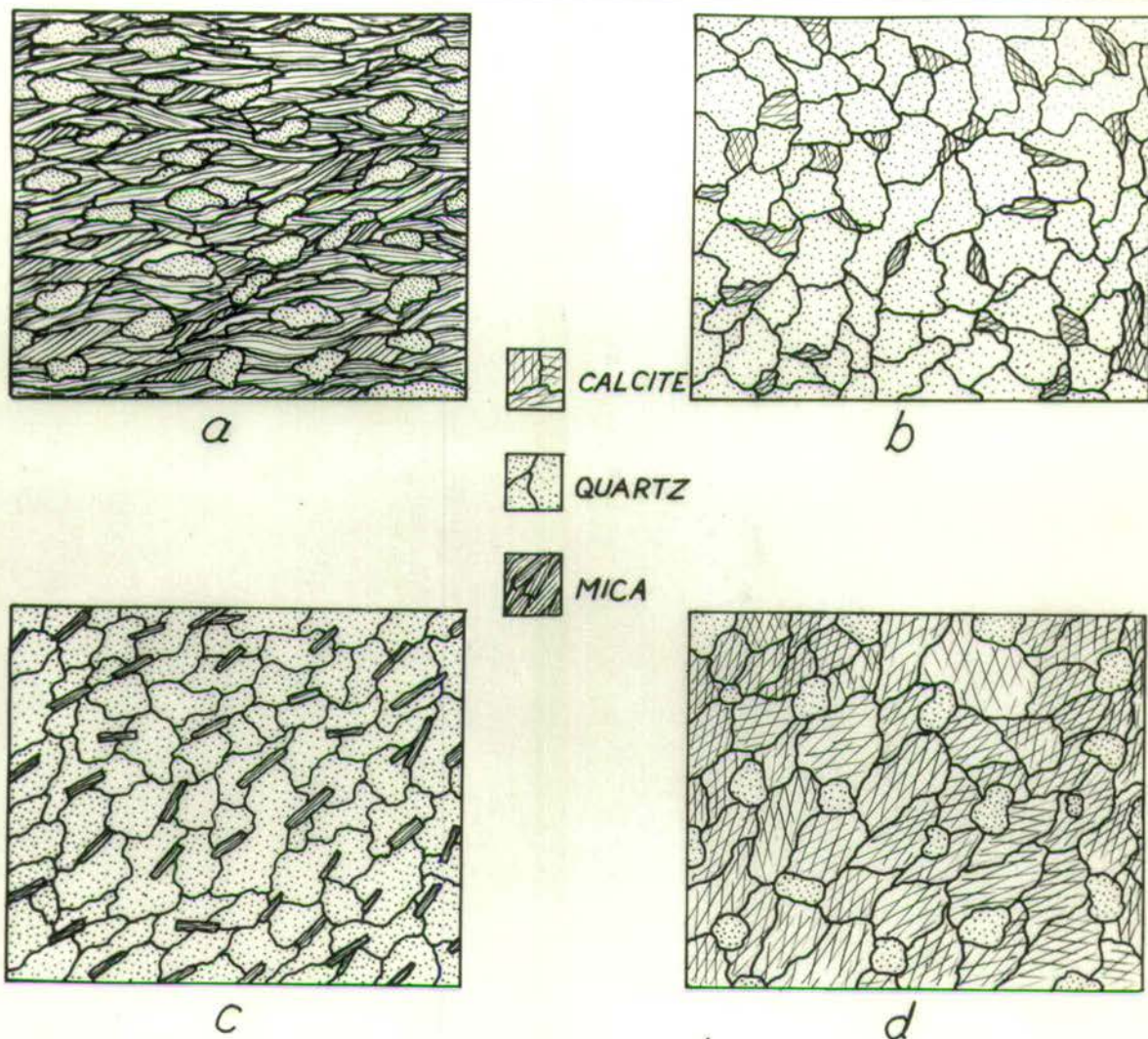


Figure 4. Diagrammatical representation of mineralogical "frameworks".

active-passive relations between mica, quartz and calcite, as follows:

a) A framework of mica with interstitial quartz; mica is active (perhaps by translation-gliding on (001) - planes); quartz is active (perhaps by limited plastic flow followed by cataclastic flow or "recrystallization-flow").

b) A framework of quartz with interstitial calcite; quartz is active, calcite is active (by twin-gliding on $\{01\bar{1}2\}$ - planes and so on).

c) A framework of quartz with interstitial mica; quartz is active, mica is passive.

d) A framework of calcite with interstitial quartz; calcite is active, quartz is passive.

Examples of (a) are given by any mica schist in which quartz shows a preferred orientation of $[0001]$ - axes. Generally the preferred orientation is weak (see, for instance, Turner, 1948, p. 212, figure 64). No published example of (b) is known to the writer, but in it both quartz and calcite would show a preferred orientation of $[0001]$ - axes. An example of (c) is the tectonite from Anglesey/

Anglesey described above. An example of (d) has been described by the writer from near Barstow, California, U.S.A. (Weiss, 1954, pp 57-58); the quartz is quite unoriented in a matrix of calcite with preferred orientation. Other relations are possible from the list of four minerals. In feldspathic gneisses with a framework of feldspar, quartz commonly shows a preferred orientation (Weiss, 1956, figure 23 1); and mica, when interstitial in calcite, behaves in the same way as when it is interstitial in quartz (Weiss, 1954, pp 57-58).

It can be seen from figures 4c and 4d that passive components, respectively, mica and quartz, do not always affect symmetry of fabric. Mica has a strong inequidimensional habit and, by its preferred orientation and positioning can define surfaces of anisotropy in a fabric. Because of this it has, generally, a preferred orientation prior to deformation (perhaps parallel to sedimentary bedding or metamorphic foliation) and a different preferred orientation (depending upon the geometry of flow in the deforming framework) after deformation. Quartz, on the other/

other hand, generally has no initial dimensional inequality (for instance as elastic sand-grains in a limestone) and no initial or final preferred orientation. Of the common rock forming minerals, mica is the only one which is likely to modify symmetry of fabric so that it disagrees with symmetry of strain. This is because it shares many of the features of a surface of inhomogeneity, even where it is structurally passive.

From the above considerations, the following general conclusions can be drawn which act as a guide in applying the principle of symmetry to naturally deformed microfabrics.

1. Symmetry of external stress is commonly modified by structural anisotropy so that strain has a lower order of symmetry. Examples of this are given by the experimentally deformed Yule marble in which an initial preferred orientation of calcite controls deformation, and by micaceous rocks in which, on a microscopic scale, flexural slip folding of the structural surface defined by the (001) - planes of mica is produced by a simple compression. In both examples external stress has axial symmetry whereas the symmetry of strain is lower (orthorhombic or monoclinic).

2. Symmetry of fabric equals symmetry of strain (penetrative movement). This holds true without exception only for structurally active components. Most structural anisotropy is active in deformation so that strain has a symmetry different from stress (1, above) but not from fabric. The experiments on Yule marble provide strong support for this view. However, if a structural anisotropy (such as a preferred orientation of isolated flakes of mica) remains passive during deformation, and if it has a geometry and symmetry which initially disagrees with symmetry of strain, then it can modify the symmetry of the resultant fabric so that it no longer agrees with symmetry of strain.

3. For the purposes of structural analysis symmetry of fabric thus is of two kinds:

a) symmetry defined by active components which always agrees with symmetry of strain; it is proposed to call this primary symmetry of fabric;

b) symmetry which is a result of the interaction of the symmetry of active components with a different symmetry of passive components, this symmetry does not agree with symmetry of strain/

strain; it is proposed to call this secondary symmetry of fabric.

In the experiments on Yule marble only primary symmetry is involved; in the tectonite from Anglesey the fabric has secondary triclinic symmetry because of orientation of passively participating mica. The principle of symmetry holds only for primary symmetry.

6. S - ACTIVE AND S - PASSIVE FLOW

So far in this discussion, concern has been only with the components involved in componental movement on a microscopic scale. Now it is intended to examine the way in which the principles of active and passive structural behaviour can be extended to structural elements on larger scales.

Flow in rocks in response to deformation is effected by componental movements of the kind described above. The symmetry of these componental movements can be studied by means of the principle of symmetry, either on the scale of the components concerned, as outlined in the last section, or on larger scales on which the components/

ponents are so small relative to the field of investigation that deformation can be considered continuous and, for certain fields, homogeneous. In fields in which flow is statistically continuous, it may be envisaged as occurring by slip on penetrative slip- or flow-surfaces which traverse a fabric in parallel sets. If the slip on each surface is uniform in direction, sense and amount, then a deformation is affine or homogeneous. If the slip varies from surface to surface the deformation is non-affine or inhomogeneous (Knopf and Ingerson, 1938, pp 75-77). In some fabrics, such slip surfaces are visibly defined by one or more parallel sets of discrete thin layers, in which movement is concentrated, separating layers in which deformation is comparatively slight (see figure 2a); whereas in other fabrics the slip surfaces do not exist as discrete surfaces or layers of inhomogeneity. Instead the surfaces are conceptual surfaces spaced on infinitesimal distance apart, but they may be defined statistically in a fabric by a preferred orientation of grains. The same criteria are/

are used to recognize affine and non-affine deformations where the slip surfaces are conceptual. It was pointed out in the section dealing with scale and homogeneity that statistical homogeneity is a function of scale, so that, depending upon the relation between the spacing of individual slip surfaces and the size of field, a field may be considered either statistically homogeneous or statistically inhomogeneous. For a small field such as a hand specimen or thin section to be considered homogeneous, the slip surfaces must be conceptual, that is, the distance between individual slip surfaces may be looked upon as being less than the average diameter of grains. Deformation, under these circumstances, is uniformly distributed by componental movement. In larger field, a statistically homogeneous deformation may be effected by slip on surfaces spaced on appreciable distance apart. For instance, slip on surfaces of "strain-slip clearance", although generally inhomogeneous on a microscopic scale, can be considered a homogeneous deformation in most field areas of moderate size. This structure/

structure is characteristic of micaceous rocks and reflects, to some extent, a behaviour typical of rocks with a framework of mica; in most tectonites, such as quartzites, marbles, feldspathic gneisses, quartz-mica schists and so on, deformation is effected by componental movements uniformly distributed through a layer of uniform composition, and conceptual slip surfaces are defined statistically by the preferred orientation, but not by the position, of grains.

Before discussing the symmetry of movements on slip surfaces, it is necessary to remember that, prior to deformation, most rocks possess a structural anisotropy in the form of a parallel set of surfaces of inhomogeneity most commonly defined by a differential compositional layering and a preferred dimensional orientation of grains. In the general case of previously undeformed rocks being deformed for the first time, this layering is sedimentary bedding or volcanic or igneous layering and, on a regional scale, it is statistically planar and horizontal. In the general case of rocks previously deformed/

deformed or metamorphosed undergoing a second deformation; this layering is a metamorphic foliation (generally derived directly or indirectly from bedding) which, although it may be planar in small fields, is not statistically horizontal. In large fields it is folded in some fashion. This set of surfaces, whatever its genetic significance, is referred to as S.

The great Swiss geologist Albert Heim once pointed out that folded mountains develop because the crust of the earth is stratified. This thought expressed the importance which must be attached in both geometrical and kinematic studies of deformed rocks to the effects upon the course of deformation of the presence of S. Not all undeformed rocks possess S; large plutonic bodies may be approximately statistically isotropic. Where such bodies are deformed by flow they cannot "fold" in the way in which layered rocks fold and consequently deform much less readily. During deformation such bodies sometimes acquire a metamorphic foliation and thereafter deform by folding.

The/

The widespread presence of flexural slip folds in layered rocks deformed by flow suggests that, in certain rocks, under certain physical conditions, S is a surface of low shear-strength and behaves as a surface of preferential slip, although the orientation of the external deforming stresses is such that the shearing stress on S is not the highest possible value. An example is given by flexural slip folding of a horizontally layered body in response to a simple horizontal compression: the shearing stress on S statistically is zero. In rocks in which a framework of mica has a preferred orientation of (001) - planes defining S, S tends to be a surface of slip under most physical conditions. But the appearance of "strain-slip cleavage" shows that other slip surfaces can operate even in rocks with a framework of mica. However, in this instance, the initial S is bodily rotated (transposed) into a new S. In rocks such as bedded sandstones, layered semipelitic gneisses or quartz-mica schists with quartz and feldspar frameworks, S may function as a slip surface under/

feldspar frameworks, S may function as a slip surface under some conditions and not under others. In rocks such as pure quartzites, limestones or marbles, with a very weak S defined by slightly impure layers, S may not be a surface of preferential slip under most conditions of deformation. The factors which control the ease with which slip on S occurs probably are as follows:

a) external physical conditions of deformation such as confining stress, temperature and chemical environment (ease of recrystallization);

b) degree of compositional heterogeneity parallel to S; if S is parallel by alternating thin layers of widely differing composition it is more likely to be a surface of slip, whatever the composition of the layers, than if there is lithological uniformity parallel to S (for instance, thinly bedded shales and sandstones fold more readily than a few thick layers of sandstone and shale);

c) in a single uniform layer, composition of the layer/

layer: S defined by preferred orientation of platy minerals such as mica, forming a framework, is more likely to be a surface of slip than where it is defined by minerals such as feldspar.

It is concluded from these considerations that two extreme conditions may be recognized in layered rocks deformed by flow:

1. Flow is conducted by slip on S as the only slip surface in a rock. S is a mechanically active structural element in this type of flow which here is termed S - active flow.

2. Flow is conducted on slip surfaces mechanically induced in a rock in a manner decided by the axes of principal stress, irrespective of the presence of S. S is a mechanically passive structural element in this type of flow which here is termed S - passive flow.

It has already been shown that whether a microscopic structural component behaves actively or passively during deformation can affect the geometry and symmetry of the resultant fabric. In the following sections/

sections the geometry and symmetry of fabrics produced by S - active and S - passive flow are examined in order to decide whether or not primary and secondary symmetry occur on large scales.

7. GEOMETRY AND SYMMETRY OF FLOW

Slip or flow surfaces can be divided into two kinds depending upon the overall symmetry of slip:

1. The slip surfaces are asymmetrically related to the axes of strain. These are called here, for convenience, asymmetrical slip surfaces.

2. The slip surfaces are symmetrically related to the axes of strain. These are called here, symmetrical slip-surfaces.

The commonest example of slip surfaces of the first kind given by the simple shear of a pack of cards. There is one set of parallel surfaces of slip upon which slip is affine or non-affine. A strain of this kind is rotational and the deforming body undergoes a rotation relative to coordinates external to it. This is termed an/

an external rotation (Knopf and Ingerson 1938, pp. 36 and 37) and is expressed in deformed rocks generally by flexural slip folding of the slip-surface. The geometry of deformation is best pictured in terms of a form ellipsoid of strain produced by homogeneous deformation of an initial sphere. This form ellipsoid (see Hills, 1953, p. 26) is not to be confused with the strain ellipsoid of elastic strain improperly cited by some geologists in describing phenomena of flow in rocks. The form ellipsoid is meant only to show the qualitative shape or form of a sphere of material after deformation. If the diameter of the initial sphere is D , then the form ellipsoid produced by affine simple shear is a triaxial ellipsoid, greatest axis A , intermediate axis B and least axis C so that,

$$A > D; \quad B = D; \quad C < D.$$

This is a biaxial strain because one axis (B) is unchanged (figure 5).

The most commonly considered example of slip surfaces of the second kind is given by equivalent slip upon two planar sets of slip surfaces symmetrically inclined/

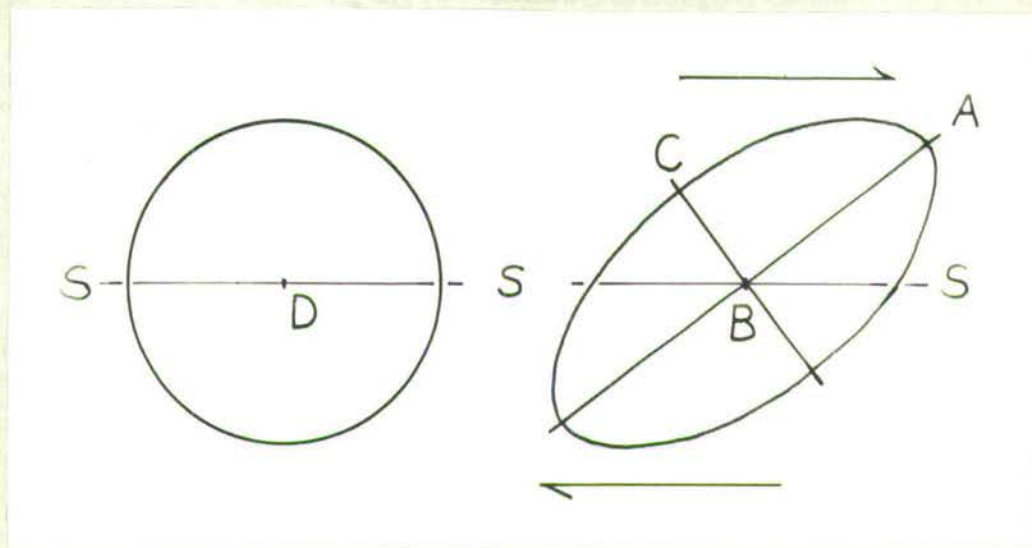


Figure 5. Biaxial strain of a sphere to a triaxial ellipsoid by affine slip on a single set of surfaces (S).

inclined to the axes of strain. The surface intersect in the axis of intermediate principal strain, and the strain is biaxial. The form ellipsoid for this deformation is, as before;

$$A > D; \quad B = D; \quad C < D.$$

But this is not the only form ellipsoid which can be produced by affine symmetrical slip. The following deformations of sphere D also can occur;

1. $A > D; \quad B > D; \quad C < D$ (triaxial ellipsoid) - triaxial strain
2. $A > D; \quad B < D; \quad C < D$ (triaxial ellipsoid) - triaxial strain
3. $A > D; \quad B > D; \quad C < D; \quad A = B$ (oblate spheroid) - triaxial strain
4. $A > D; \quad B < D; \quad C < D; \quad B = C$ (prolate spheroid) - triaxial strain.

The last two are special cases with axial symmetry of strain and are neglected in the present discussion. There remain two form ellipsoids of triaxial strain.

The dynamic identity of flow surfaces in rocks is beyond the scope of this paper, but it is certain that no triaxial strain can be achieved by slip upon two planar sets/

sets of symmetrical slip surfaces. Only a biaxial strain can arise in this fashion. Either four sets of planar slip surfaces are involved ($(h0l)$ and $(0kl)$ - surfaces, as suggested by Sander, 1948, p. 82) or the surfaces are not planar but have the form of conceptual elliptical cones symmetrically placed relative to the axes of strain. The identity of these surfaces is immaterial in a discussion of symmetry.

Triaxial and biaxial strains by symmetrical slip can be either rotational or non-rotational depending upon whether external stress is, respectively, rotational or non-rotational. The rotation is an external rotation of the whole field of deformation and leaves no imprint in the symmetry of the deformed body. If this external rotation is neglected, the symmetry of strain is orthorhombic, in contrast to biaxial strain by asymmetrical slip (simple shear) which is a monoclinic strain, with or without external rotation. Also, asymmetrical slip is monoclinic whether it is affine or non-affine.

Strain by symmetrical slip can acquire lower symmetry/

symmetry than orthorhombic if slip on the sets of symmetrically placed slip surfaces is non-equivalent. Irregularities of this kind are common in small fields and are reflected in the slight degree of asymmetry common in patterns of preferred orientation of active structural components on a microscopic scale (for instance, patterns or preferred orientation of $[0001]$ - axes in a quartzite). Such departures from ideal symmetry are usually slight and statistically insignificant on a large scale. For what follows, only equivalent symmetrical slip is considered.

S - active flow always corresponds, in a small field where S is planar, to asymmetrical slip (pure shear). But, once again, scale is all important; if a very large field is considered, in which S is a surface of flexural slip on a small scale, then the opposing limbs of flexural slip folds may correspond in a very broad fashion to two planar sets of symmetrical slip surfaces. For this to be so the folds must be so small relative to the field considered that deformation is statistically homogeneous.

In/

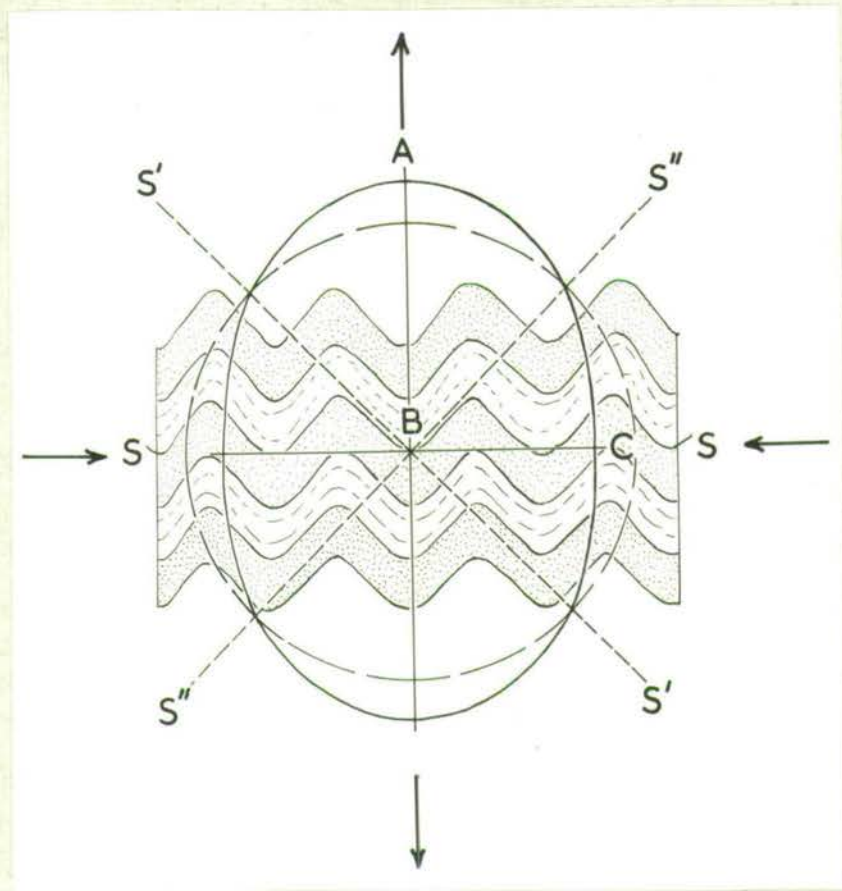
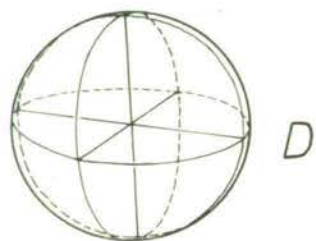


Figure 6. Flexural slip folding of S as a biaxial strain by symmetrical slip on S' and S'' in a field of very large size.

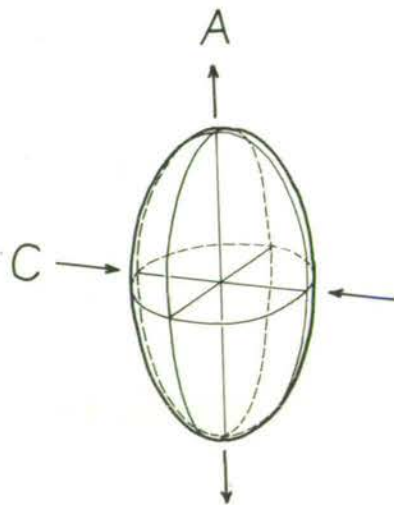
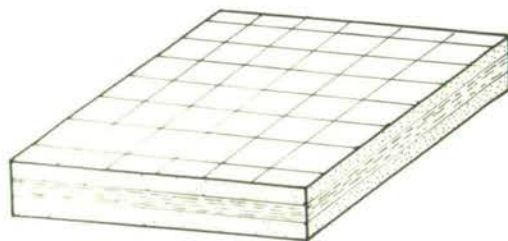
In figure 6 is shown diagrammatically a body of rock deformed in this fashion by flexural slip of S. The two sets of statistically planar limbs correspond, in effect, to intersecting planar slip surfaces, S' and S'', which rotate towards the axial plane of the folds with progressive deformation in the same way as planar slip surfaces rotate towards the limiting plane which bisects one angle between them.

In figure 7a a horizontally layered body is represented in its undeformed state by a sphere of diameter D. The body is subjected to a horizontal squeezing (Einengung, Sander, p. 68) so that it deforms by S - active flow, and the folds which form are so small relative to the field considered that the deformation is statistically homogeneous. The form ellipsoid $A > D$; $B = D$; $C < D$ can be taken to represent the external biaxial strain of the body (figure 7b). Although on a small scale the flexural slip movements are monoclinic (figure 7b, lower), on the scale of the whole field the external strain is statistically orthorhombic (figure 7b, upper). Similarly, if the strain becomes triaxial so that there are two horizontal directions of/

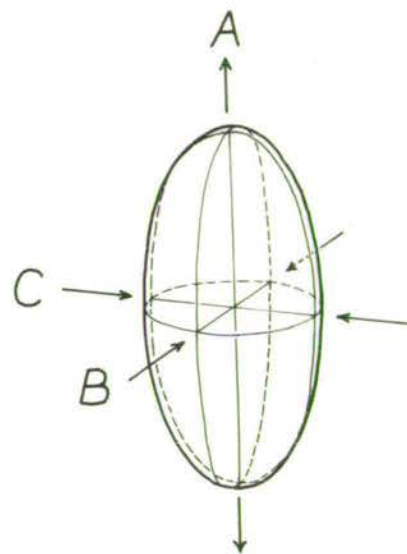
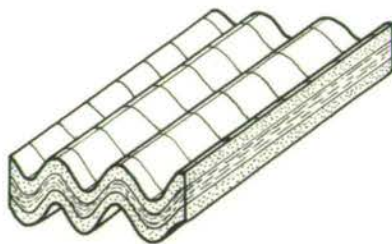
Figure 7. Diagrammatical representation of biaxial strain (b) and triaxial strain (c) of an initially horizontally layered body (a), where greatest and mean axes of principal strain are horizontal. The form ellipsoids represent external strain of the body on a scale where strain is statistically homogeneous.



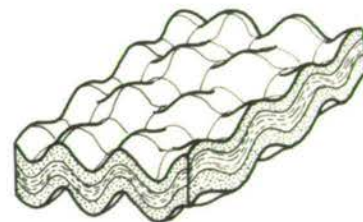
a



b



c



of squeezing (form ellipsoid $A > B$; $B < C$; $C < D$), then S - active flow produces folds and cross folds (Querfaltung; see, for instance, Koark, 1952, pp. 253, 254) which have internal triclinic symmetry of strain on a small scale (figure 7c, lower). Once again, if these folds are so small relative to the size of the whole deformed body that deformation is statistically homogeneous, then the external strain is statistically orthorhombic (figure 7c, upper).

On a much smaller scale, the same principles are involved in the experiments on Yule marble. Each grain of calcite in the marble has translation planes which act as surfaces of monoclinic slip; but because the grains are small relative to the size of the deformed specimen, the deformation is statistically homogeneous and the external strain of the specimens has generally axial or orthorhombic symmetry. Some grains deforming synchronously by several kinds of gliding mechanism even have triclinic symmetry of strain, but this does not affect the symmetry of external strain of the whole specimen.

S - active flow can, according to scale, represent either/

either asymmetrical or symmetrical slip, as defined above.

In S - passive flow, S undergoes geometrical transformations which depend upon the orientation and symmetry of the slip surfaces. In general, S is rotated through the fabric, in a more or less regular fashion, as slip occurs. Such a rotation is termed an internal rotation (Knopf and Ingerson, 1938, pp. 36 and 37) because it is a rotation relative to coordinates within the deforming body. The geometry of internal rotation depends largely upon the symmetry of the slip surfaces. The straightforward case of internal rotation of a planar structurally passive surface by slip on a single set of planar slip surfaces has been used by Turner, Griggs and Heard (1954) in detailed analyses of structures produced in single crystals of calcite by experimental deformation. The geometry of internal rotation of a passive surface and any line within it is shown in figure 8 (from, Weiss, 1955) modified from Borg and Turner (1953, figure 3). The rectangular prism ABCDEF contains a randomly oriented/

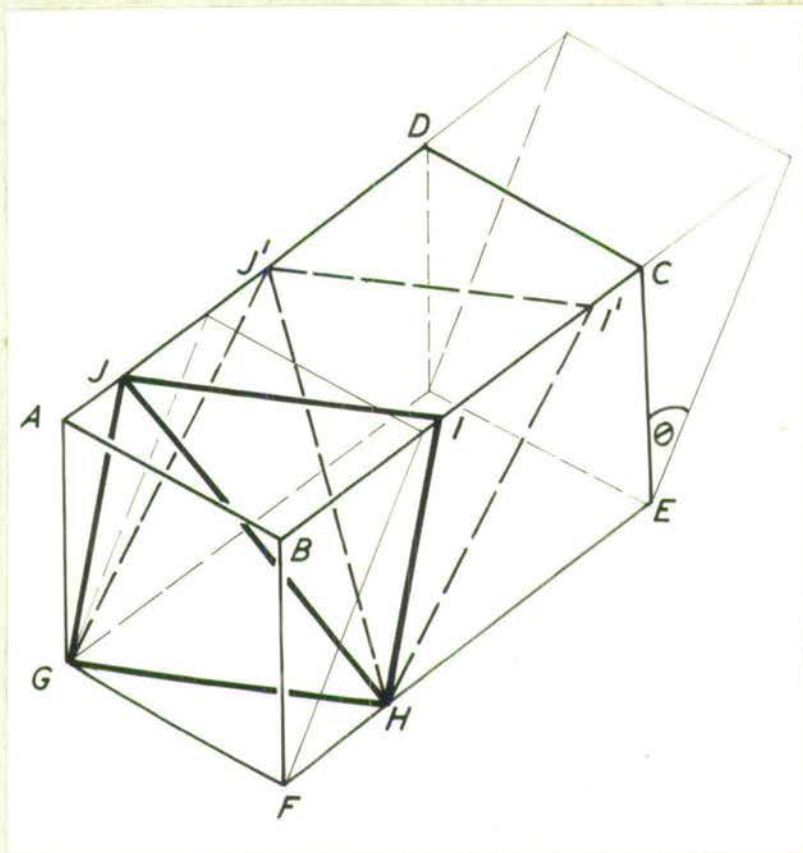


Figure 8. Internal rotation of a passive surface (GHIJ) and line (HJ) by affine slip on a single set of surfaces parallel to ABCD.

oriented surface GHIJ which in turn contains a line HJ. The prism is deformed by affine slip in direction AD on surfaces parallel to ADCB; the angle of shear is θ .
 is internally rotated
 The surface GHIJ about the axis GH to the position GHI'J', and the line HJ is internally rotated to HJ'. No matter how great the amount of deformation J' always lies on AD (the direction of slip) and HJ is internally rotated so that it always lies in the unique plane containing its initial position and the direction of slip. Thus, the axis of internal rotation of a surface is the axis of intersection of the surface with the slip plane, whereas the axis of internal rotation of a line is the normal to the plane containing the line and the direction of slip. So long as deformation is affine, the passive surface (S) remains planar. But if deformation is non-affine, then cylindroidal folds in S can be produced. The fold axis is the axis of internal rotation of S (F.A. in figure 9a) Such folds are called slip folds.

If S is cylindroidally folded before deformation the fold is internally rotated in the same fashion as a line/

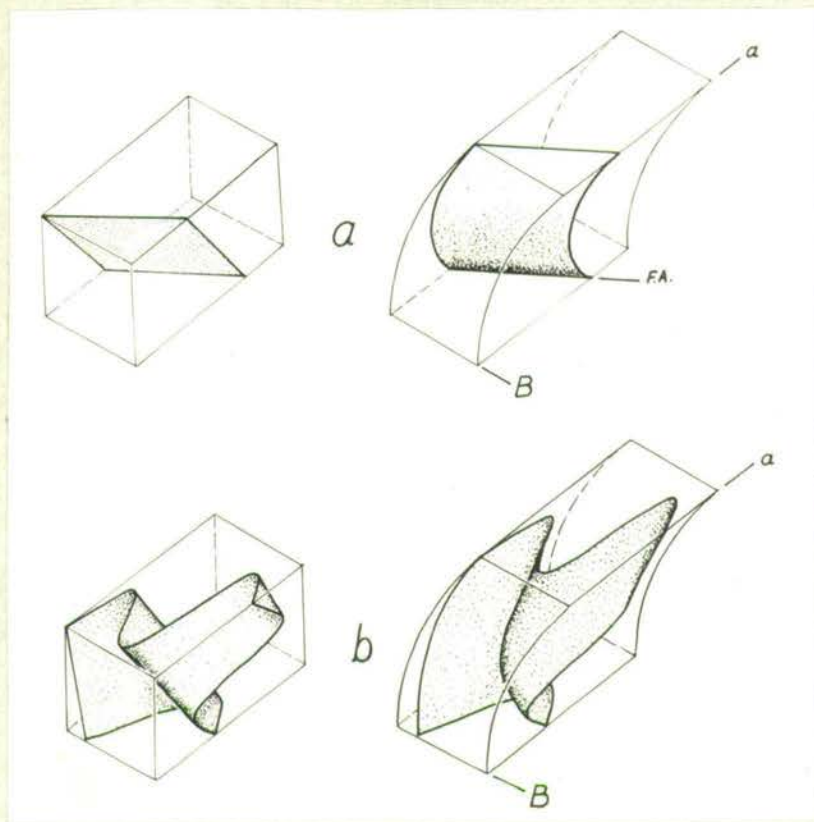


Figure 9. Internal rotation of passive structures by non-affine slip on a single set of surfaces.

a. An initially planar surface.

b. An initially folded surface.

line. If deformation is affine, the fold axis remains straight and the folds remain cylindroidal, but they change their degree of appression in a manner decided by the relative orientation of the fold axis and the slip surfaces. If deformation is non-affine, the fold axis becomes bent and subsidiary slip folds can be formed in limbs of the first folds (figure 9b). The fold axis remains in one plane (the plane containing its initial position and the direction of slip).

In all the foregoing examples the symmetry of strain is monoclinic whether deformation is affine or non-affine. It can be assumed that the symmetry of active microscopic components (especially the framework of the fabric) has acquired this symmetry, according to the principle of symmetry. But without exception, the overall symmetry of the fabrics is triclinic because the passive element S has not acquired the symmetry of the movements. This triclinic symmetry is secondary symmetry.

From these considerations it may be concluded that passive structural elements have the ability to produce secondary symmetry lower than symmetry of strain, on/

on all scales in rocks deformed by flow. S - passive flow is likely to produce fabrics with secondary symmetry, S - active flow can never do so; but not all S - passive flow produces secondary symmetry that is lower than symmetry of strain. In the special case where a set of planar slip surfaces intersects a passive S parallel to the axis of slip in the slip surfaces, the secondary symmetry is monoclinic and agrees with the symmetry of strain because the axis of internal rotation coincides with the axis of slip. This relationship is particularly important in rocks deformed initially by S - active flow, giving rise to flexural slip folding of S, in which further deformation in response to the same pattern of stresses produces S - passive flow in certain layers. The outer layer of the fold shown in figure 10 flows S - actively throughout a phase of deformation; but the inner layer deforms initially by S - active flow and subsequently, as deformation proceeds, by S - passive flow, so that it fails on a single set of slip surfaces (S'), subparallel to the axial plane of the fold, in the sense shown. This deformation/

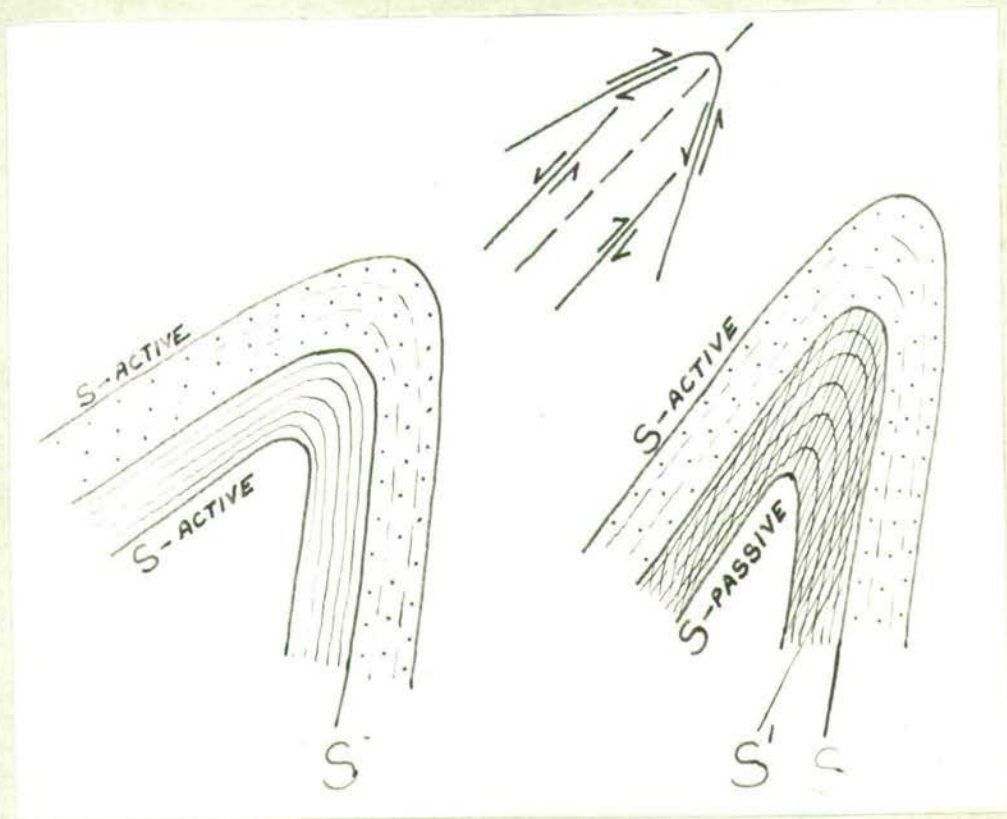


Figure 10. Simultaneous S-active and S-passive flow in adjacent layers of differing mechanical properties.

deformation by \underline{S} - passive flow is non-affine on the scale of the whole fold, and folding of the inner layer continues by slip folding. The axis of the slip fold (the intersection between \underline{S} and \underline{S}') is parallel to the axis of flexural slip in the layer deformed by \underline{S} - active flow so that the symmetry of the whole fold is monoclinic. The inner layer has evolved through a phase of \underline{S} - active flow to a phase of \underline{S} - passive flow with the same symmetry.

So far, the only kind of \underline{S} - passive flow considered is that produced by slip on a single set of surfaces. Slip on symmetrical surfaces, either planar or non-planar, can also produce internal rotation of passive \underline{S} . It is impossible to determine the geometry of internal rotation of a passive \underline{S} by symmetrical slip as simply as it is by asymmetrical slip for two main reasons:

1. The orientation and identity of the surfaces of slip is a matter of conjecture.
2. It is certain that the surfaces of slip change their orientation during progressive deformation of a given body.

Also, the amount of internal rotation of a passive/

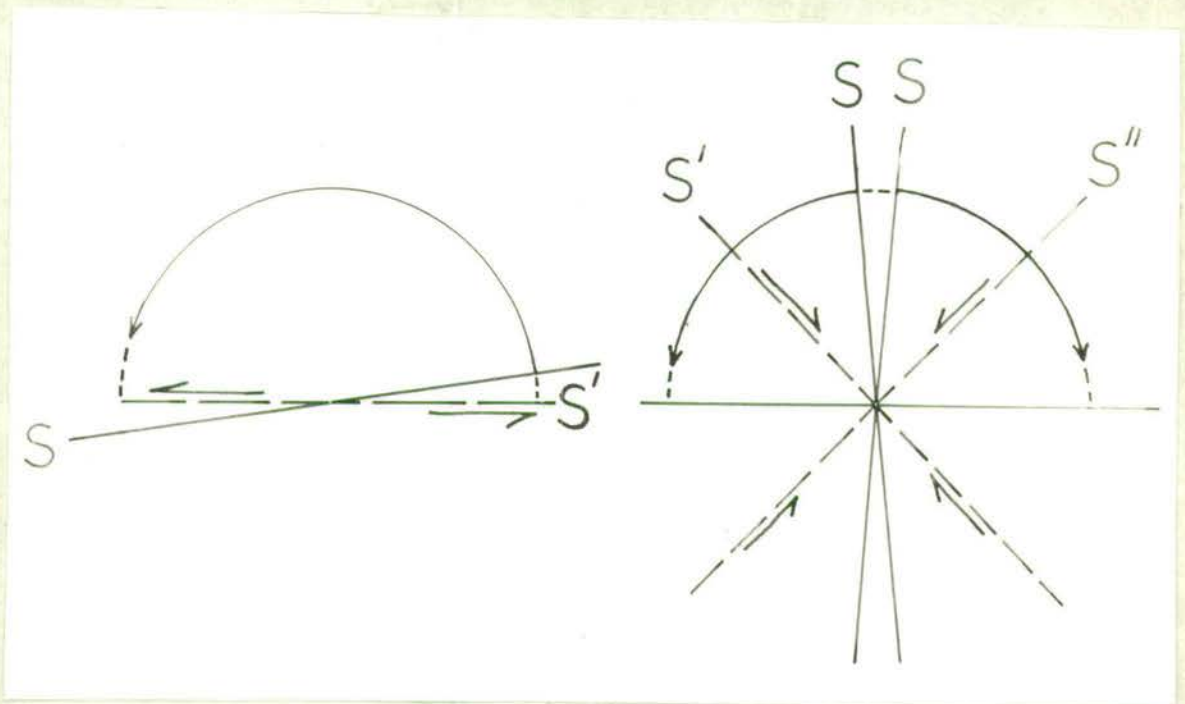


Figure III. Maximum angles of internal rotation of a passive planar surface (S) by asymmetrical and symmetrical slip.

passive S that can be produced by symmetrical slip is limited. The internal rotation of suitably oriented S by slip on a single set of surfaces ideally can approach 180° because S is rotated in the same sense no matter what angle it makes with the slip surface (S' in figure 11a). By symmetrical slip, S is rotated in different senses depending upon its initial orientation relative to the slip surfaces (S' and S'' in figure 11b). Internal rotation of suitably oriented S by symmetrical slip can therefore approach only 90° . However, whatever may be the identity and orientation of symmetrical slip surfaces, the following conclusions regarding internal rotation of S are probably valid for affine strain:

1. An initially planar S remains planar.
2. If S initially is cylindroidally folded, the fold axis remains linear and the fold limbs become more appressed.
3. All orientations of S approach parallelism with the plane AB of the form ellipsoid (the surface of "flattering", see Turner, 1948, pp. 166 to 168).

The/

The most important case of internal rotation of passive S by symmetrical slip concerns another evolutionary sequence in which a rock deforms initially by S - active flow (flexural slip folding) in response to an external biaxial strain (figure 12a). The limbs of the folds are oppressed until the shearing stress on S falls so low that slip can no longer continue. The folds then are closed to S - active flow and S is "neutralized" as a surface of preferential slip. Further deformation in response to the same pattern of stresses can occur only if flow becomes S - passive. If the conditions of deformation and the nature of the rock are suitable, symmetrical slip surfaces are induced in the fabric; and if in addition, strain remains biaxial, these surfaces probably are planar and intersect in the axis of intermediate principal strain which is also the axis of flexural slip folds.

The symmetrical slip surfaces are thus arranged symmetrically with respect to the fold produced by S - active flow (figure 12b). Slip on S' and S'' internally rotates the limbs of the fold towards the "surface of flattening"/

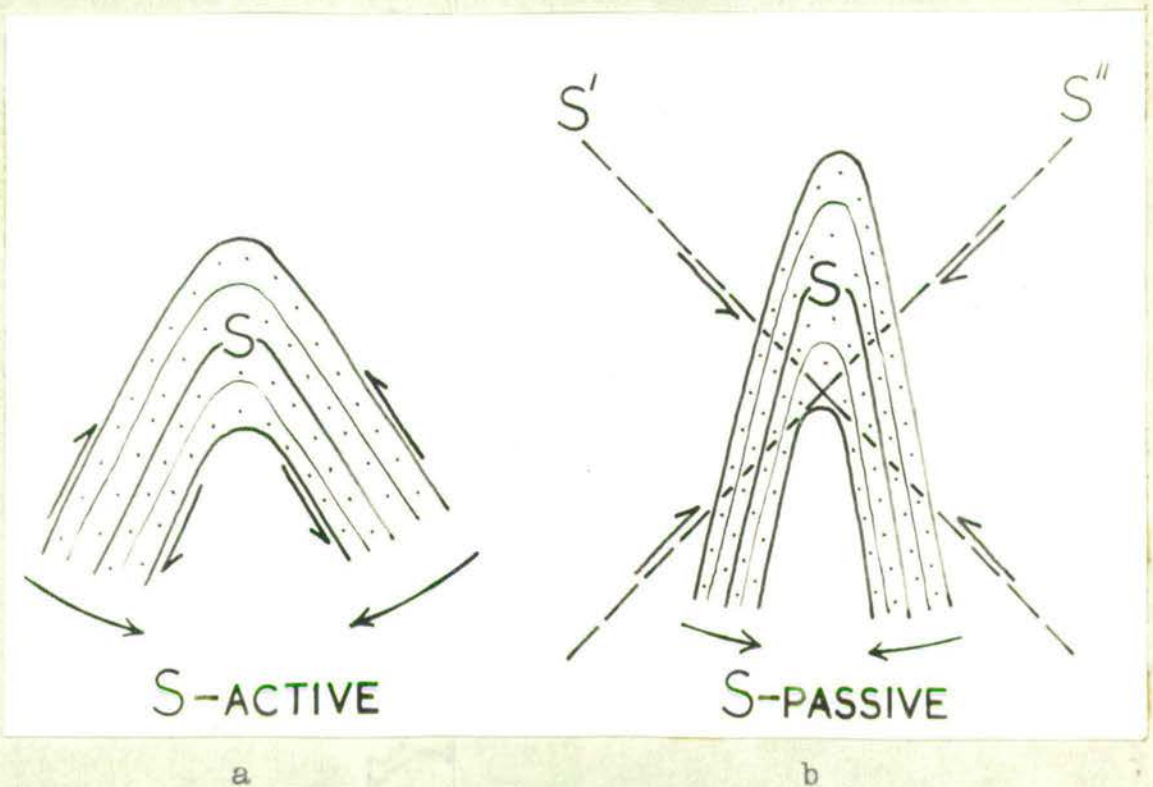


Figure 12. Transition from S-active flow (flexural slip folding) to S-passive flow by symmetrical slip with increasing statistical homogeneity of deformation.

flattening" which is the axial plane of the folds. The fold becomes a type of slip fold. The symmetry of the strain in the phase of S - active flow is monoclinic on a small scale (it has already been shown that it could be orthorhombic on a very large scale) and the symmetry of the fabric at the end of that phase is primary monoclinic symmetry. The fabric of the fold is inhomogeneous because slip on S is non-affine, and the movements can be reversed by unbending the fold. The symmetry of strain in the phase of S - passive flow is orthorhombic on all scales, and the deformation is affine. But the overall symmetry of fabric at the end of the phase of S - passive flow, is still monoclinic and inhomogeneous, because the folded passive S modifies the symmetry of strain. But the symmetry of active components (such as the quartz or calcite framework in respectively an impure quartzite or marble) is orthorhombic and homogeneous. The overall symmetry of the fabric is secondary monoclinic symmetry but the movements can no longer be reversed by unbending the fold.

Flexural/

Flexural slip folds of the first kind have been called by Sander "unrollable" folds (Sander, 1951), and slip folds of the second kind seem to correspond with "non-unrollable" folds (for examples of these kinds of fold from the Scottish Highlands, see Weiss, McIntyre and Kürsten, 1955). A non-unrollable fold can evolve out of an unrollable fold in a single act of deformation as flow passes from S- active to S - passive.

8.

FABRIC AXES

The introduction into this discussion of fabric axes has been delayed because an understanding of the significance and use of these axes in structural analysis is impossible without some knowledge of the different types of symmetry found in deformed rocks. The axes employed by most structural geologists are the orthogonal a -, b(B) - and c - axes initially proposed by Sander (1926, p. 328). No really comprehensive definition of fabric axes for fabrics with differing symmetry exists in the English language, and it is doubtful if, even today, the full philosophical content of Sander's initial purpose in/

in defining these axes has become apparent to the bulk of English-speaking structural geologists. For this reason, great care must be exercised in using these terms. To continue sprinkling papers with references to a -, and b - axes the significance of which is imperfectly understood by the writers themselves can lead only to confusion and worthless argument. In Britain and Scandinavia, in particular, futile controversy on the subject of a - and b - lineations in the rocks of the Caledonides has occurred from time to time over a period of years. In the view of the writer this controversy arose out of a lack of appreciation, on the part of the geologists involved, of the importance of the symmetry of fabric in kinematic interpretation, and a confusion of fabric axes with kinematic axes.

Fabric axes are used to describe geometry and symmetry of fabric, and they correspond, in most fabrics, to an identical set of kinematic axes which describe movements. These axes are primarily defined respectively for (1) fabrics with monoclinic symmetry, and (2) movements with monoclinic symmetry. The definitions favoured/

favoured by the writer are as follows (Weiss, 1955, p. 229):

"1. ab is the principal fabric plane. This is the most prominent surface in the fabric, that is, the foliation. The symmetry plane (which, since symmetry is monoclinic, must be normal to ab) is ac and the normal to the plane of symmetry is b. In many deformed rocks ab is folded with b as fold axis. Since b is therefore a direction of maximum continuity in the fabric it is designated B.

"2. The kinematic axes are defined for rotational strain involving slip upon one a - plane. The slip plane is ab, the deformation plane is ac and the normal to the plane of deformation is b. The direction of slip is a. Deformation is commonly by flexural slip of ab, and b, as the axis of external rotation, is again a direction of maximum continuity designated B."

From these definitions the following conclusions can be drawn for fabrics with monoclinic symmetry:

1. Foliation invariably contains the B - axis and is/

is normal to the \underline{ac} - plane. This does not mean necessarily that the foliation is a surface of slip.

2. The axes of flexural slip folds are invariably parallel to the \underline{B} - axis.

3. Lineations are either parallel to the \underline{B} - axis or they are parallel to the \underline{a} - axis.

The recognition of fabric axes in fabrics with monoclinic symmetry is straightforward. Where flow is \underline{S} - active the \underline{B} - axis always lies in \underline{S} ; and where flow is \underline{S} - passive and symmetry monoclinic, the \underline{B} - axis also lies in \underline{S} . But where flow is \underline{S} - passive and strain monoclinic (simple shear) the \underline{B} - axis can lie in the slip surface at an angle to its intersection with \underline{S} (Weiss, 1955, p. 234). The symmetry of such fabrics is not monoclinic but secondarily triclinic.

All flexural slip folds have axes which are \underline{B} - axes; in spite of this fact, which is tacit in the definition of a \underline{B} - axis, statements like the following still occur in the literature of structural geology (Kvale, 1953, p. 71): "More detailed information on folds/

folds 'in a' will be given in another paper" It cannot be stressed too strongly that no axes of flexural slip folds are parallel to a - axes in fabrics with monoclinic symmetry. Although the axes of slip folds in passive S produced by non-affine simple shear on S' can have orientations other than parallel to a B - axis, the fabrics in which they occur always have secondary triclinic symmetry (Weiss, 1955, p. 231) and, also, the one orientation that the axes of these folds never can have is parallel to an a - axis. But flexural slip folds, and thus the great bulk of similar folds in deformed rocks are always parallel to B - axes in fabrics with monoclinic symmetry. In the same paper (1953, p. 52) Kvale gives the following outline of Sander's view of the principle of symmetry; "The critical test for Sander's theory would be to apply it to an area where the direction of movement can be determined with absolute certainty from the field evidence The real testing areas..... are those where there is no doubt as to the direction of the movements involved and as to the symmetry of the structures that resulted from these movements." The particular interest in/

in this passage lies first, in the vagueness with which the term "direction of movement" is used (a usage by no means confined to Kvale), as if there were but one kind of strain in deformed rocks (presumably a kind of simple shear) which always can be described in terms of a single direction of movement; and second, in the implication that this direction of movement "can be determined with absolute certainty from the field evidence" which presumably does not include field evidence of symmetry given by the statistical preferred orientation of foliation, folds, lineation and other penetrative structures produced by strain. Kvale is enthusiastic about directions of movement and his enthusiasm has coloured his view of fabric axes which should be established from a study of geometry and symmetry (not from a study of directions of movement) and used to establish kinematics.

The problem which has confronted Kvale probably is the same one which has confronted geologists working in the Highlands of Scotland, namely the difficulty of recognizing fabric axes in fabrics with triclinic symmetry on/

on a large scale. In the Scottish Highlands (and perhaps also in Scandinavia) it is becoming increasingly obvious that many fields on a large scale have triclinic symmetry. Lineations occur widely with great variety of orientation and degree of regularity. Most of these lineations are, on a small scale, demonstrably fabric B - axes. In spite of this fact, attempts have been made to interpret them as a - lineations in order to fit the lineations into a kinematic interpretation already made on some other grounds. Anderson's (1948) contribution to the problem is concerned not so much with fabric axes as with kinematic axes; but he considers in detail a type of lineation common in the Highlands and elsewhere in bodies of rock deformed by flow which he calls the "Tummel type" of lineation. He interprets this lineation as an a - lineation parallel to a kinematic a - axis, that is, a direction of slip on a single set of slip surfaces. The description of this lineation given by Anderson (1948, p. 101) shows that it is a structure with monoclinic symmetry, and there is no doubt that the lineations, mullions/

mullions and small folds he describes are parallel to B - axes as defined above. With this fact there can be no argument. However, Anderson puts forward the view that these lineations are parallel to the "direction of shear", in other words a kinematic a - axis. Although Anderson supports his view by drawing analogies between flow in rocks and "canal flow" in fluids, it seems to the writer that his real reason for considering these to be a - lineations becomes apparent in the following paragraph (p. 101):

"These folds may be large enough to be mappable, but it should not be assumed that they are parallel, in any district, to the main system of folding. The mullion structures of North-West Scotland are well known, and one series of these is found above the Moine Thrust, in the Moine schists of Strath Oykell. They here run west-north-west, while the strike, and the main folds, are in a perpendicular direction."

From this passage it is evident that Anderson has extended his field of investigation from the scale of/
of/

of the lineations, mullions and small folds to the scale on which the "main system of folding" becomes apparent. Recent work in the Highlands is at last affording evidence of the existence of folds on a large scale upon which folds on a smaller scale are superposed (Sutton and Watson, 1954) and it is probable that the "main system of folding" envisaged by Anderson exists in certain parts of the Highlands. However, the fundamental objection to Anderson's view that the lineations and small folds are \underline{a} - axes does not rest upon the existence or non-existence of large folds with lineations of different trend superposed on the limbs, but upon the fact that Anderson extends his investigation from a small field with obvious monoclinic symmetry to a large field with obvious triclinic symmetry yet still attempts to use the fabric and kinematic axes defined for monoclinic symmetry.

In order to appreciate the significance of fabric axes in fabrics with primary triclinic symmetry, some features of the deformations which produce these fabrics must/

must be considered. Fabrics with primary triclinic symmetry are of two main kinds, first, those produced by a single non-plane deformation, and second, those produced by a superposition of two or more unrelated deformations. For the present, concern is only with the first kind.

9. TRICLINIC STRAIN

A single triclinic deformation is best envisaged in terms of two synchronous monoclinic deformations in which the deformation planes are mutually perpendicular (Sander, 1948, pp. 73 - 83). From a regional point of view it is suggested that most triclinic structures arise in the following way. A body with a planar horizontal layering (S) can be homogeneously strained by horizontal squeezing either biaxially or triaxially. If it is assumed that flow is S - active, then biaxial strain produces flexural slip folds of S and the fabric has monoclinic symmetry (figure 7b). Similar folds together with "cross-folds" are here ascribed to triaxial/

triaxial strain of the same body so that there is a subsidiary axis of shortening (c.f. Sander, 1948, pp. 180 - 181), as shown in figure 7c. The strain and the fabric have triclinic symmetry. The relation between the size and form of the interfering folds depends upon a number of factors. In figure 7c they are shown of similar size and form suggesting that the two squeezings are of a similar intensity and acted synchronously. But, commonly in rocks it is observed that the two sets of folds are expressed very differently. Whatever the form of the folds their axes lie respectively in two mutually perpendicular planes (B and B' in figure 13). Some possible interrelations in form of the interfering folds are shown diagrammatically in figure 13, as follows:

Figure 13 a; Large folds with axes in B; lineations in B'.

Figure 13 b; Large folds with axes in B; small folds with axes in B'.

Figure 13 c; Large folds with axes in B; large folds with axes in B'.

Figure 13 d; Small folds with axes in B; large folds with axes in B'.

Figure/

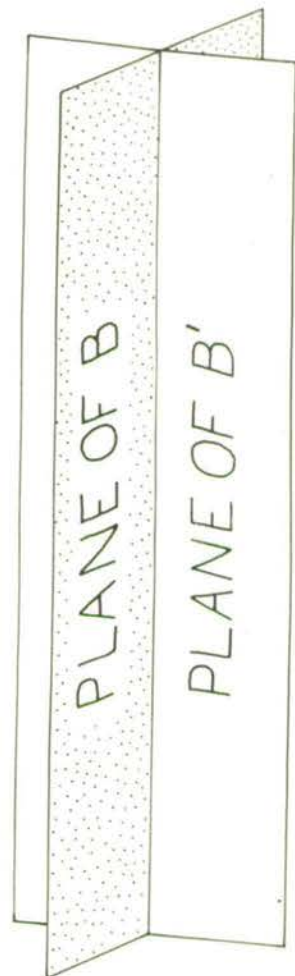
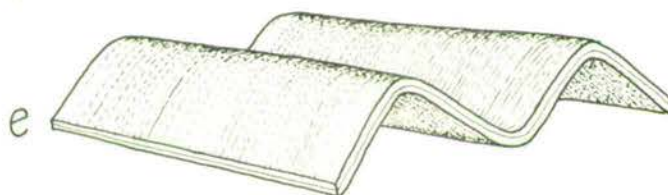
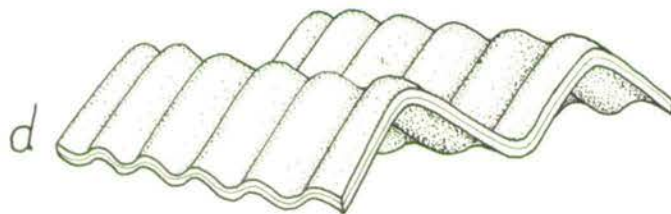
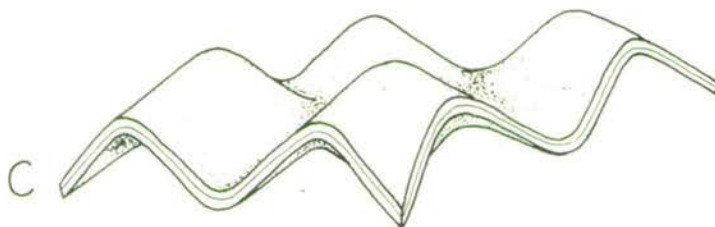
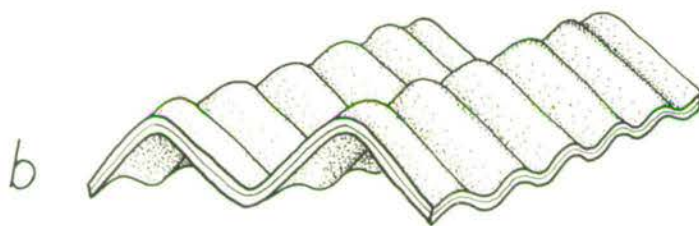
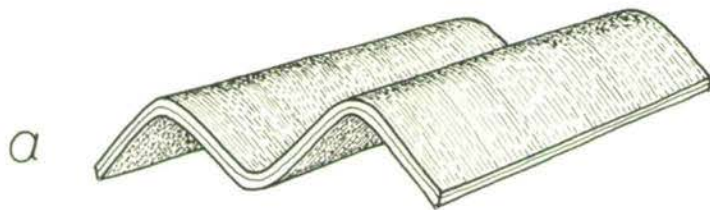


Figure 13 e; Lineations in B; large folds with axes in B'.

Figures 13a and 13e and figures 13b and 13d are geometrically identical.

Generally, one set of folds is much larger and more open than another. Because large folds require relatively great freedom of movement in a vertical direction for their formation, whereas lineations and small scale cylindroidal structures suggest restricted movement under great confining stress, it is probable that the larger folds in triclinic structures are initiated first in a phase of essentially biaxial strain with monoclinic symmetry and the smaller folds are initiated later when strain is markedly triaxial. The two types of fold can continue to form synchronously once their general form is fixed.

Whatever may be the size and form of these flexural slip folds, their axes are B - axes. Each B - axis is normal to one of the two axes of squeezing and for a planar orientation of S the two B - axes are mutually perpendicular/

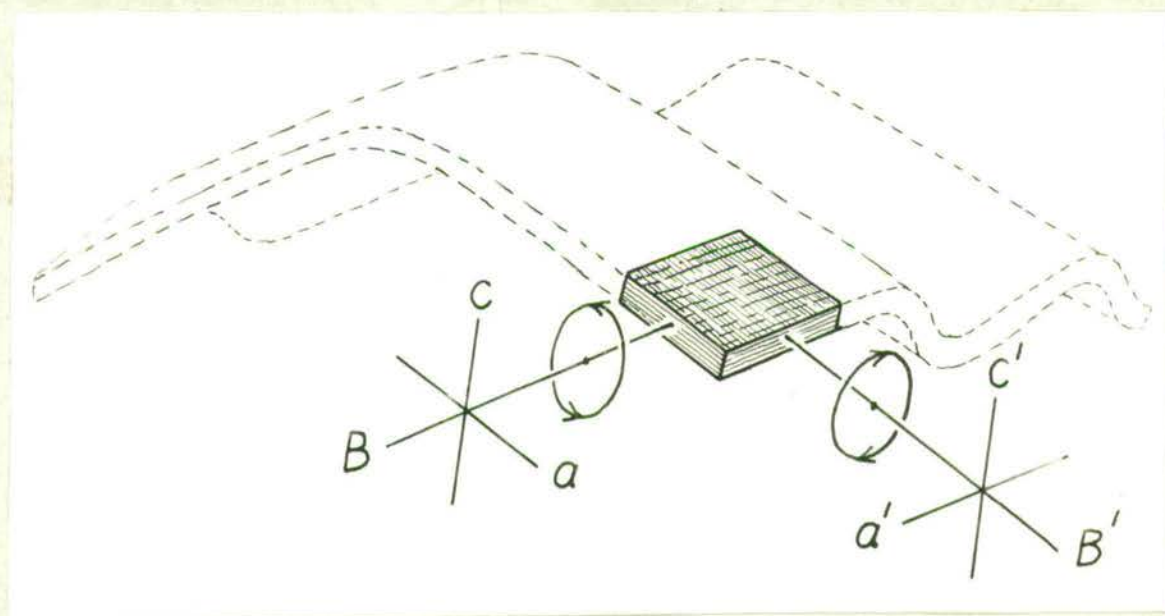


Figure 14. Resolution of triclinic strain into two mutually perpendicular monoclinic strains ($\underline{B} \perp \underline{B}'$).

perpendicular. In a large field, the axes lie in two mutually perpendicular planes as shown in figure 13. In figure 14 is shown a portion of a triclinic structure in which S is planar. Each B - axis is paralleled by a lineation which, in the formation of the triclinic structure, is an axis of rotation in the sense shown. It is possible to define a - and c - axes for each of the monoclinic movements represented by the B - axes. a, B and c are the kinematic and fabric axes for one phase and a', B' and c' for the other. It can be seen from figure 14 that a is parallel to B', B is parallel to a' and c is parallel to c'. The symmetry of the fabric and the movements can be described in terms of the two B - axes only. Such a fabric is called a B \perp B' - tectonite (Sander 1948, p. 82). There is no fundamental difference on genetic grounds between B and B' and it is immaterial which axis is labelled B and which B'. Figure 13 is an attempt to show this fact in diagrammatic form. In some rocks, one axis is much more prominent than the other. The Swiss Alps, for instance, have an obvious axis of large scale folding that/

that is labelled B; but the depression and culminations in the plunge of this axis, which probably reflect a degree of triaxial strain, give rise to large, open flexures in the limbs of the nappes, with axes normal to B. These may be looked upon as B' - flexures. In parts of the Scottish Highlands one axis is expressed as plunging folds on the limbs of large, open folds. Locally, only this second axis can be detected by geometrical means in a small field. Which of these axes is labelled B and which B' is not important. Movement parallel to the axes of first formed folds of large size may be less intense and penetrative than the movements that formed the later small scale structures.

Anderson (1948, pp. 120 - 122) comments upon Sander's view that triclinic movement can be resolved into two syngenetic monoclinic movements (slip in mutually perpendicular directions on the same slip surface) and suggests that such movements would be expressed in the form of a single oblique monoclinic slip. His view is based upon the assumption that the monoclinic movement involved/

involved is a simple shear. This is not so on most scales in deformed rocks. Flexural slip is more important than planar slip when the field of more than one limb of a fold is considered. Fold axes which form parallel to each \underline{B} - axis control the possible directions of slip down to the smallest scale and no resultant slip oblique to \underline{B} and \underline{B}' is possible. Also, Sander points out that the two deformations (about \underline{B} and \underline{B}') are not simultaneous but act alternately in small overlapping phases.

Anderson's picture, in the Scottish Highlands, of large folds with horizontal axes and small folds and lineations superposed parallel to the dip of the limbs suggests a $\underline{B} \perp \underline{B}'$ - structure. Both axes are demonstrably \underline{B} - axes and the symmetry of the whole structure is triclinic and not monoclinic as Anderson seems to suppose. The \underline{a} - axis, as defined for monoclinic symmetry, is not used to describe fabrics with triclinic symmetry. The large folds with horizontal axes envisaged by Anderson in parts of the Highlands have left no penetrative trace of their/

their existence either because this trace has been overprinted by the more intense componental movements which produced the plunging B - structures, or because the large folds formed initially without componental movement and are not tectonitic. This is apparent because the field of one dipping sheet of rock, corresponding, according to Anderson, to one planar limb of a large fold, can have monoclinic symmetry on all scales within it and not the triclinic symmetry expected of B₁ B' - tectonites. The only B - axis demonstrable on grounds of symmetry in such a field is that parallel to the plunging folds, mullions and lineations; a dipping sheet does not mean necessarily the presence of a horizontal fold axis parallel to the strike. It is possible that a similar state of affairs to that described in the Highlands exists also in Scandinavia. The criticisms of the principle of symmetry made by both Anderson and Kvale probably stem from attempts to determine kinematics in large fields with primary triclinic symmetry from fabric/

fabric axes determined in small fields with monoclinic symmetry. Fields deformed triaxially have no large scale "direction of shear" (kinematic a - axis), and more than one B - axis may be developed in a single strain.

However, insufficient work has been done in the Highlands to establish whether, on the scale of the whole deformed body, the area is to be considered one of B \perp B' - tectonics or of the B \wedge B' - tectonics to be described below.

10. ORTHORHOMBIC STRAIN

On a small scale, orthorhombic strains can be produced only by S - passive flow. Consequently, fabrics with primary orthorhombic symmetry are relatively rare because most rocks only enter a phase of S - passive flow after passing through a phase of S - active flow, and S commonly imparts secondary monoclinic or triclinic symmetry to the orthorhombic symmetry of active components. The fabrics of layered rocks tend to follow, during progressive deformation, definite evolutionary sequences which/

which depend upon the nature of the rocks, the physical conditions of deformation and the nature of the deforming stresses. The first phases of deformation tend to produce inhomogeneous strain by S - active flow, of the kind described in the last section, until S is "neutralized" as a surface of slip by flexural slip folding. If the stresses remain unchanged in orientation and intensity, ~~the~~ further deformation is impossible without S - passive flow. This can make its appearance in different rocks at different times, in a single field of deformation; but, for a large uniformly stressed field, the form ellipsoid of strain for a phase of S - active flow can be considered to coincide exactly with the form ellipsoid of strain for S - passive flow. This is why a homogeneous imprint in the framework of a microfabric generally bears a symmetrically relation to structures produced in a previous phase of inhomogeneous deformation.

All deformations by S - active flow on symmetrical surfaces have orthorhombic symmetry of strain, if/

if external rotation of the whole field of deformation, where external stress is rotational, is neglected. It is impossible, using the same criteria used for monoclinic and triclinic strains and fabrics, to define either kinematic or fabric axes for orthorhombic symmetry. However most fabrics, as outlined above, enter a phase of orthorhombic strain by \underline{S} - passive flow after previously passing through a phase of genetically connected \underline{S} - active flow. The structures produced in the fabrics by \underline{S} - active flow (folds and cross-folds in \underline{S}) remain in the fabric as passive structures and prevent the fabrics from acquiring overall orthorhombic symmetry. Using these structures it is possible to modify the axes as used for monoclinic and triclinic strains for use in homogeneous orthorhombic imprints so that they retain much of their kinematic significance on a large scale. This can be done because on a large scale, deformation by \underline{S} - active flow can have statistical homogeneity, and the structure produced by \underline{S} - active flow can have orthorhombic symmetry. The three mutually perpendicular planes of symmetry defined, on a large scale, by the statistical orientation of small scale structures/

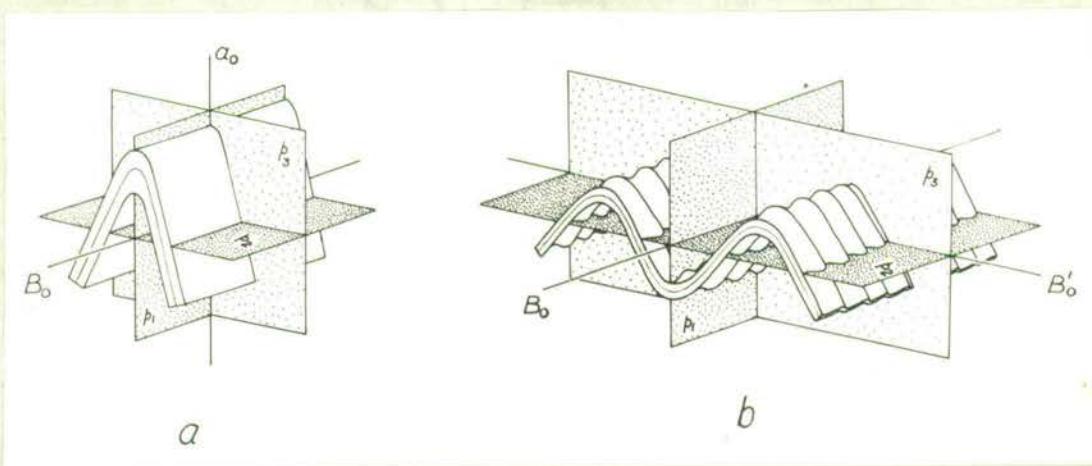


Figure 15. Relation of three planes of symmetry (p_1 , p_2 and p_3) of orthorhombic imprints in active structural components to structures in passive S during an earlier phase of syngenetic S-active flow.

structures have a symmetrical relation to these structures on all scales. Likewise, homogeneous orthorhombic strains (either biaxial or triaxial) by S - passive flow have three mutually perpendicular planes of symmetry, here called p_1 , p_2 and p_3 , which are reflected in the homogeneous orthorhombic structural imprint on all scales. Where a phase of homogeneous deformation by S - passive flow follows a genetically related phase of S - active flow (heterogeneous on a small scale), the orientation of p_1 , p_2 and p_3 with respect to the small scale structures produced by S - active flow is as shown diagrammatically in figure 15. For biaxial orthorhombic strain, p_1 and p_2 intersect in the axis of the flexural slip folds formed in the phase of S - active flow, and one of them (p_1) is parallel to the axial plane of the folds (figure 15a). The other is normal to the fold axis (E - axis of the monoclinic phase). The intersection between p_1 and p_2 is the E - axis (E_o) of the orthorhombic strain and of the homogeneous orthorhombic imprint in active structural components, and it/

it coincides with the \underline{B} - axis of the monoclinic structures. The axis normal to \underline{B}_0 in \underline{p}_1 is termed the \underline{a} - axis (\underline{a}_0 in figure 15a). This usage does not correspond exactly with the usage for monoclinic symmetry because the \underline{aB} - plane is not parallel to surfaces of slip in the orthorhombic strain; also, the \underline{a} - axis for the monoclinic phase is not parallel to the \underline{a} - axis for the orthorhombic phase, although they both lie in the same plane (\underline{p}_3).

For triaxial orthorhombic strain ($A > D$; $B < D$; $C < D$) there is even less obvious relation between the fabric axes ($\underline{B} \perp \underline{B}'$) for the triclinic phase of \underline{S} - active flow (heterogeneous on a small scale) and the axes of intersection of the three planes \underline{p}_1 , \underline{p}_2 and \underline{p}_3 for the orthorhombic phase of \underline{S} - passive flow (homogeneous on all scales). The orientation of the structural elements on a macroscopic scale is shown in figure 15b. \underline{p}_1 coincides with the plane of \underline{B} and \underline{p}_3 with the plane of \underline{B}' (see figure 13). On a macroscopic scale, \underline{B} and \underline{B}' can have a variety of orientation in \underline{p}_1 and \underline{p}_3 ; they are not always parallel to the intersections of \underline{p}_1 and \underline{p}_3 with \underline{p}_2 . However, on a very large/

large scale where the inhomogeneities caused by the development of $\underline{B} \perp \underline{B}'$ - structures are insignificant, \underline{B} and \underline{B}' are statistically linear and do coincide respectively with the intersections between \underline{p}_1 and \underline{p}_2 and between \underline{p}_2 and \underline{p}_3 . These may be called \underline{B} - axes (respectively \underline{B}_0 and \underline{B}'_0) of the orthorhombic structural imprint although the plane in which they lie is not parallel to a surface of slip, and, in most small fields, they do not coincide with the \underline{B} - and \underline{B}' - axes of the triclinic phase of \underline{S} - active flow.

In some fabrics a phase of orthorhombic strain by \underline{S} - passive flow does not follow an earlier phase of \underline{S} - active flow: such fabrics can have primary orthorhombic symmetry on all scales. An example of such a fabric is a horizontally layered body deformed by a vertical squeezing or an unlayered body deformed by either a vertical or a horizontal squeezing. No \underline{S} - active flow is possible in either instance because, in the first, the shearing stress on \underline{S} is zero and, in the second, no \underline{S} is present. \underline{S} - passive flow by symmetrical slip produces in/

in such fabrics a homogeneous orthorhombic imprint in active components the symmetry of which is not changed by the orientation of passive structures.

If strain is biaxial such fabrics can be orthorhombic \underline{B} - tectonites, as described above, and, if it is triaxial, orthorhombic $\underline{B} \perp \underline{B}'$ - tectonites.

11. KINEMATIC EVOLUTION

From the features of tectonite - fabrics already discussed in this paper, it is possible to draw the following conclusions:

1. From an initially undeformed fabric, a given system of stresses can produce tectonite - fabrics with great variety of geometry and symmetry, depending upon the mechanism of deformation within the fabric.

2. A given system of stresses can produce statistically homogeneous strain of a large body even where deformation is inhomogeneous on a small scale. In other words, either \underline{S} - active or \underline{S} - passive flow can produce an external strain which is statistically homogeneous on a large scale.

- 3./

3. A given system of stresses acting over a long period of time can produce a uniform statistically homogeneous strain of a body which deforms, on a small scale, by different mechanisms as deformation proceeds. In this fashion a fabric on a small scale can evolve kinematically so that it possesses, at successive stages, different geometry and symmetry.

4. A fabric can deform either by \underline{S} - active or \underline{S} - passive flow. For most rocks, \underline{S} - active flow probably passes into \underline{S} - passive flow as deformation proceeds.

5. External strain of a large body can be either biaxial or triaxial and either rotational or non-rotational. Also, strain can pass from biaxial to triaxial, or from non-rotational to rotational with progressive deformation.

On the basis of these conclusions, it is possible to examine in a broad fashion some of the lines of kinematic evolution which a horizontally layered body undergoing a first deformation can follow. In order to do this it is necessary to make some basic assumptions with regard to unbalanced stresses external to the body in/

in the crust of the earth, as follows:

1. Stress is either two dimensional or three dimensional, corresponding, in a statistically homogeneous deformation, respectively to biaxial and triaxial strain.

2. Where stress is non-rotational, one axis of principle stress is vertical and two are horizontal (see, Anderson, 1951, p. 12). If the axis of greatest principal stress is labelled \underline{P} , then there are two possible orientations of \underline{P} ;

a) \underline{P} is horizontal

b) \underline{P} is vertical.

3. Where stress is rotational, owing to the action of a force-couple, the plane of the force-couple is either vertical or horizontal.

An external rotational stress produces rotational strain of a body if deformation is statistically homogeneous; but, if strain is by symmetrical slip (which, on a large scale can include \underline{S} - active flow by flexural slip folding - figure 6), then only an external rotation of the whole field of deformation distinguishes the symmetry and/

and geometry of the structures produced by external rotational stress from those produced by external non-rotational stress. This rotation is about either a horizontal axis (if the force-couple acts in a vertical plane) or about a vertical axis (if the force-couple acts in a horizontal plane). In what follows, only the effects of non-rotational stress are considered.

On the basis of these assumptions some lines of kinematic and structural evolution of a uniformly stressed horizontally layered body are shown diagrammatically in figure 16. The external strain of the whole body, on a scale where strain is statistically homogeneous, is given in terms of the three axes (A, B and C) of a form ellipsoid of strain produced by deformation of an initial sphere of diameter D. Features of macroscopic fabric at stages in kinematic evolution are shown diagrammatically and the type of symmetry at each of these stages is recorded. In the phase of \underline{S} - active flow the symmetry of active microscopic structural components is monoclinic or triclinic and macroscopically inhomogeneous; in the phase of \underline{S} - passive/

passive flow the symmetry of active microscopic structural components is orthorhombic and homogeneous on all scales. It must be stressed that the passage from S - active to S - passive flow shown by some lines of evolution is not synchronous in lithologically different members of a heterogeneous body. Some members may deform entirely by S - active flow. An example is given by a highly micaceous rock in which S is defined solely by the preferred orientation of (001) - planes of mica. In such a rock, S, instead of becoming passive, is transposed by folding into a new S so that the (001) - planes never become passive as surfaces of slip. Other rocks can deform entirely by S - passive flow (for instance, a uniform limestone or marble with S defined by scattered and mechanically inactive layers of heavy minerals); and others may pass from S - active to S - passive flow as deformation proceeds (most rocks probably fall into this category). Figure 16 is intended to outline in a qualitative fashion the behaviour of a body with an overall composition similar to most heterogeneous geosynclinal/

Figure 16. Idealized lines of kinematic evolution followed by the fabric of an initially horizontally layered body in response to horizontal squeezing (explanation in text).



BIAXIAL

TRIAxIAL

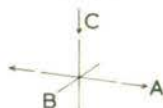
P ⊥ S

P || S

P ⊥ S

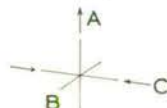
P || S

S - ACTIVE

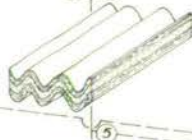


1 3

3

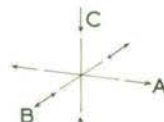


4 5 6



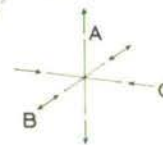
$A > D; B = D; C < D:$

PRIMARY MONOCLINIC SYMMETRY



2

2



7

8



$A > D; B > D; C < D:$

PRIMARY MONOCLINIC SYMMETRY



$A > D; B < D; C < D:$

PRIMARY TRICLINIC SYMMETRY

S - PASSIVE



$A > D; B = D; C < D:$

PRIMARY ORTHORHOMBIC SYMMETRY



$A > D; B = D; C < D:$

SECONDARY MONOCLINIC SYMMETRY



$A > D; B > D; C < D:$

PRIMARY ORTHORHOMBIC SYMMETRY



$A > D; B > D; C < D:$

SECONDARY MONOCLINIC SYMMETRY



$A > D; B < D; C < D:$

SECONDARY TRICLINIC SYMMETRY

INCREASING "STATISTICAL HOMOGENEITY" OF DEFORMATION

synclinal bodies of sedimentary rock.

From an initially horizontal and planar S, eight lines of kinematic and structural evolution have been pictured in figure 16, as follows:

1. Strain is biaxial and P is normal to S.

Shearing stress of S is zero so that no deformation is possible by S - active flow; deformation by S - passive flow has orthorhombic symmetry and produces fabrics with primary orthorhombic symmetry in which passive S agrees in symmetry with the active components on a microscopic scale.

2. Strain is triaxial and P is normal to S. No deformation is possible in the field of S - active flow; S - passive flow produces two kinds of strain depending upon the geometry of the form ellipsoid. Both types of fabric have primary orthorhombic symmetry, although the identity of the symmetrical surfaces of slip is different in the two cases.

3. The line joins 1 and 2 representing a transition from biaxial to triaxial strain.

4./

4. Strain is biaxial and P is parallel to S.

Flexural slip folds form in the phase of S - active flow with axes parallel to B of the form ellipsoid ($A > D$; $B = D$; $C < D$), which thus is also a fabric B - axis; movement is monoclinic on a small scale and fabric has primary monoclinic symmetry. In field of S - passive flow, symmetrical planar flow surfaces, intersecting in B of form ellipsoid further appress folds by internal rotation of limbs; symmetry of active microscopic structural components becomes orthorhombic but fabric has secondary monoclinic symmetry.

5. Conditions are as in 4, but at the end of the phase of S - active flow, strain becomes triaxial so that the form ellipsoid is $A > D$; $B > D$; $C < D$. No triaxial strain of this kind is possible by S - active flow because no extension along a fold axis can be achieved by slip on S; but in the field of S - passive flow the folds are further appressed by internal rotation (the fold axes as in 4, remain parallel to B of the form ellipsoid) as a result of slip upon symmetrical flow surfaces (not two planar sets), and the body also extends parallel to the fold/

fold axis. A deformation of this type has been called axial flow by the writer (Weiss, 1954, p. 76) because it results in flow along an already formed fold axis. The symmetry of the active structural components becomes orthorhombic and the symmetry of the fabric becomes secondary monoclinic symmetry.

6. Conditions are as in 4, but, near the end of the phase of S - active flow, strain becomes triaxial so that the form ellipsoid is $A > D$; $B < D$; $C < D$. The shortening of the body parallel to B of the form ellipsoid (fold-axis of flexural slip folds produced by biaxial strain) causes cross-folds to develop by slip on S, in the manner outlined above, so that on a macroscopic scale strain is triclinic (B⊥B') and the fabric has primary triclinic symmetry. Passage to S - passive flow changes the symmetry of strain on all scales to orthorhombic; but fabric has secondary triclinic symmetry because of the B⊥B' structures in the passive S. The folds and cross-folds are further oppressed by complex phenomena of internal rotation.

7. Strain is triaxial and P is parallel to S.

The/

The form ellipsoid of strain is $A > D$; $B > D$; $C < D$. As in 5, no triaxial strain is possible for this form ellipsoid by \underline{S} - active flow. The three dimensional stress system produces only biaxial strain by \underline{S} - active flow in the form of flexural slip folds with primary monoclinic symmetry. In the phase of \underline{S} - passive flow, as in 5, extension along the already formed fold axis (axial flow) is accompanied by further shortening normal to the axial planes of the folds. The active structural components acquire orthorhombic symmetry on all scales and symmetry of fabric becomes secondary monoclinic symmetry.

8. Strain is triaxial and \underline{P} is parallel to \underline{S} .

The form ellipsoid of strain is $A > D$; $B < D$; $C < D$. Folds and cross-folds form synchronously in the phase of \underline{S} - active flow ($\underline{B} \perp \underline{B}'$ - structure) by triclinic macroscopic strain, and fabric has primary triclinic symmetry. Transition to phase of \underline{S} - passive flow converts the symmetry of active components to orthorhombic, on all scales, internally rotates the passive \underline{S} in a complex fashion and produces secondary triclinic symmetry of fabric.

Figure/

Figure 16 is intended to stress in simplest terms the evolutionary nature of many fabrics of deformed rocks. It is not suggested that the figure contains even most of the lines of kinematic and structural evolution possible for an initially horizontally layered body deformed by flow; and any one line of evolution can be diverted at any point by a complete change in the nature of the deforming stresses. But, for a uniform system of stresses, the most important omission in the diagram is that no account is taken of structures produced by rotational strain. It has already been pointed out that one type of rotational strain is the same as non-rotational strain with an added external rotation of the whole field of deformation with reference to coordinates external to the field of deformation. But there is another kind of rotational strain. Anderson (1948, p105) has written with respect to strain in the crust of the earth on an orogenic scale; "The writer thinks it is admitted that there are two important processes which play a part in orogeny, with many others, probably, which cannot be so easily/

easily defined.

a) The first consists in a lateral compression, with an increase in the vertical dimensions of the body of rock which is affected. The folds produced by this process have axial planes which are nearly vertical, and the nature of the distortion is shown by vertically elongated pebbles and fossils. It is this, also, which gives rise, in the main, to slaty cleavage, in planes which have, again, a tendency to be vertical.

Lineation may be present as a sort of striation, which sometimes runs in an up-and-down direction along the cleavage planes.....

b) The second is exemplified by Alpine Nappes and other recumbent folds, and consists of relative movement which is, typically, horizontal.

Expressed in kinematic terms, the first type of distortion is roughly a pure strain, while the second is more nearly represented by a simple shear, with one set of plane surfaces unaltered in direction. In the first case there are evident limits to the possible amount of deformation/

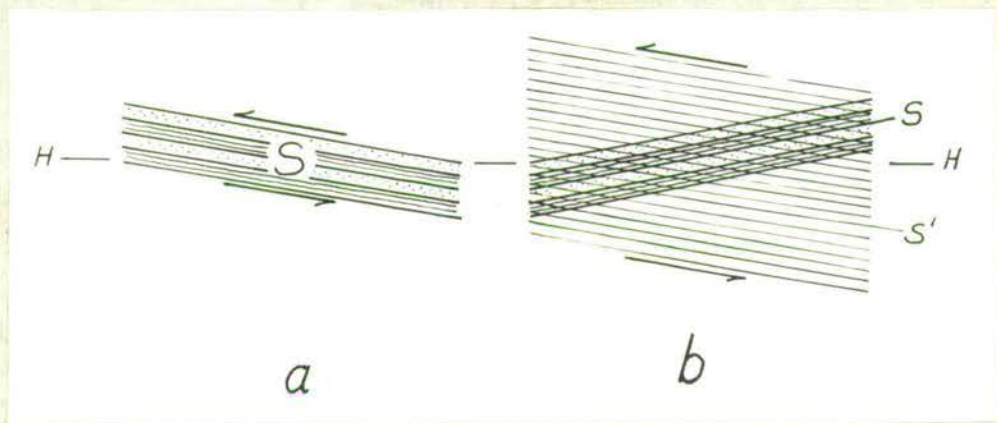


Figure 17. Unrestricted transport by,
a. S-active flow.
b. S-passive flow.

deformation, while in the second there is much greater freedom of movement."

The first type of movement envisaged by Anderson corresponds to restricted transport (Fairbairn, 1949, pp. 215 - 218) and is characterized by symmetrical slip, even where strain is rotational. The evolutionary lines depicted in figure 16 are all products of restricted transport because, on a large scale, slip is on symmetrical slip surfaces, even where flow is S - active (figure 6). The second kind of movement envisaged by Anderson corresponds to unrestricted transport (Fairbairn, 1949, pp. 218 - 222) and has monoclinic symmetry on all scales with or without external rotation of the whole field of deformation. It is characteristic of a shallower~~er~~ progenic level than restricted transport. A deformation represented by a simple shear must have, on all scales, "one set of plane surfaces unaltered in direction," and must be biaxial. For flow to be S - active, the set of plane surfaces must be S, and deformation is by planar slip on S (figure 17a). S - passive flow involves the mechanical induction of a single/

single set of planar slip surfaces (\underline{S}'), which thus are asymmetrical to the strain axes, intersecting \underline{S} in a horizontal axis (figure 17b). The most likely system of stresses to produce this kind of strain is either horizontal \underline{P} or a force couple acting in a vertical plane. Either of these systems produces slip on \underline{S}' in a direction normal to its horizontal intersection with \underline{S} . Affine slip on \underline{S}' produces internal rotation of \underline{S} about its axis of intersection with \underline{S}' , as explained by figure 8. Non-affine slip on \underline{S}' can produce slip folds of \underline{S} so that the fold axis coincides with the axis of internal rotation and the kinematic \underline{B} - axis of the deforming movements.

Fabrics and movements on all scales and at all stages in kinematic evolution of this kind have monoclinic symmetry.

12. SUPERPOSED DEFORMATIONS

The fabrics of many deformed rocks are products of kinematic evolution in a single prolonged phase of deformation, as outlined in the last section, and can be structurally analysed with little difficulty; but the fabrics of some deformed rocks have triclinic symmetry and/

and complex geometry indicating a long evolutionary history involving more than one phase of strain corresponding to essentially unrelated orogenic impulses. These successive phases of movement can differ amongst themselves in symmetry and orientation of kinematic axes. In some fabrics, a last phase of intense penetrative movement completely obliterates structures produced by earlier phases, thereby falsely implying for the fabrics a simple evolution; but, not uncommonly, fabrics occur in which there is only partial overprinting of structures produced in one phase of movement by structures produced in other phases. By systematic analysis of structural data from such fabrics, sometimes it is possible to establish a sequence of unrelated tectonic events (in the same fashion as sequences can be established for a single deformation, as outlined in the last section) and thereby to reconstruct earlier periods in the structural history of the rock. Such reconstructions may be possible for fields ranging in size from single crystals in thin section to bodies of folded rock in orogenic zones.

Earlier in this discussion it was pointed out that/

that some fabrics have triclinic symmetry produced by superposition of two unrelated phases of strain. Many strongly deformed rocks fall into this class. The time interval between deformations can be small or great: the deformation may be successive phases of one orogenic deformation separated by relatively short periods of time during which relative rotation, or perhaps change in relative importance of axes of principal stress, occurred; or the deformations may be separated by relatively long periods of time, as is true for rocks involved in successive unrelated orogenic deformations.

For the purpose of what follows, the time-relations and genetic relations of successive deformations ^{un}are/important because concern is only with geometry and symmetry. However, the number of deformations which can be superposed one upon the other, and still leave a readable trace of their activities in the form of visible structures, probably is limited. It is rarely indeed, that the structural history of a rock which has suffered more than two phases of penetrative movement can be fully deciphered/

deciphered. For this reason, only superposition of two deformations is considered here; and, because concern is finally with structural analysis on an orogenic scale, the first deformation is considered to act upon essentially undeformed rocks with planar and horizontal \underline{S} . It is proposed to examine in a qualitative fashion the geometrical transformations of $\underline{\tilde{S}}$, from its initial horizontal orientation, likely to be produced by two superposed unrelated strains. There are possible an infinite variety of transformations depending upon the type of strain, the type of flow, the scale of observation and so on. In order to limit this discussion, certain assumptions regarding stress and strain are made as follows:

1. Stress is either non-rotational or rotational; if it is non-rotational, \underline{P} is horizontal; if it is rotational, \underline{P} moves in a vertical plane (force couple acting in a vertical plane). These stresses correspond, broadly, respectively to tangential squeezing and tangential shearing, probably the most common types of orogenic stress on a large scale in the crust of the earth.

2./

2. \underline{S} - active flow corresponds either to symmetrical slip (on a scale where deformation is statistically homogeneous) or to asymmetrical slip: strain by \underline{S} - active flow can be either non-rotational or rotational. \underline{S} - passive flow corresponds either to symmetrical slip or to asymmetrical slip: strain by \underline{S} - passive flow can be either non-rotational or rotational.

3. Strain is either biaxial or triaxial. Only one case of triaxial strain (where $A > D$; $B < D$; $C < D$) is considered because the other case (axial flow) does not produce fabrics with triclinic symmetry.

4. Because strain is statistically homogeneous in a large field, biaxial strain is represented by the axis of greatest principal stress (\underline{P}_1 and \underline{P}_2 respectively for the first and second strains) which coincides with the axis of least principal strain. Triaxial strain similarly is represented by the axes of greatest and intermediate principal stress ($\underline{P}_1, \underline{P}'_1$ and $\underline{P}_2, \underline{P}'_2$ respectively for the first and second strains), which coincide respectively with axes of least and intermediate principal strain. The axes of the second strain are inclined to the axis of the first/

first.

5. The first strain is by \underline{S} - active flow; the second strain is by either \underline{S} - active or \underline{S} - passive flow.

6. Between the first strain and the second there can be an external rotation of the field of deformation with reference to the horizontal.

The procedure followed in determining the transformations of \underline{S} is the reverse of that followed in the techniques of kinematic unrolling (Ruckformungen) and levelling (Horizontierung) used by Sander (1948, pp. 170 to 172). \underline{S} is assumed initially to be planar and horizontal and is transformed by strain, in a diagrammatic fashion, in terms of the lower hemisphere of an equal area projection. The representation of fields homogeneous with respect to \underline{S} and \underline{B} can be made in terms of Π - and β - diagrams; or a statistically regular orientation of \underline{S} can be represented on the projection as a great circle, and a statistically regular orientation of \underline{B} as a single point. Difficulty is encountered in representing fields with triclinic/

triclinic symmetry because of the great variety of orientation that S and B can have in such fields. The following graphical conventions are used in the diagrams:

1. Cylindroidal flexural slip folds are represented by a series of great circles (S₁, S₂, S₃ and so on) intersecting in the fold axis (B).

2. A triclinic B⊥B' - structure is represented by two great circles, one normal to P and one normal to P', which are the planes respectively of B and B' structures (lineations, mullions and small folds) produced by triaxial strain and S - active flow. It is impossible to represent on a single projection, in terms of ΠS - poles and B - axes, a triclinic structure in which the folds are large with reference to the field of investigation. A triclinic field can only be represented on a large scale where structure is statistically homogeneous.

3. A homogeneous orthorhombic imprint in active components produced by S - passive flow is represented by great circles corresponding to three planes of symmetry P₁, P₂ and P₃.

Large/

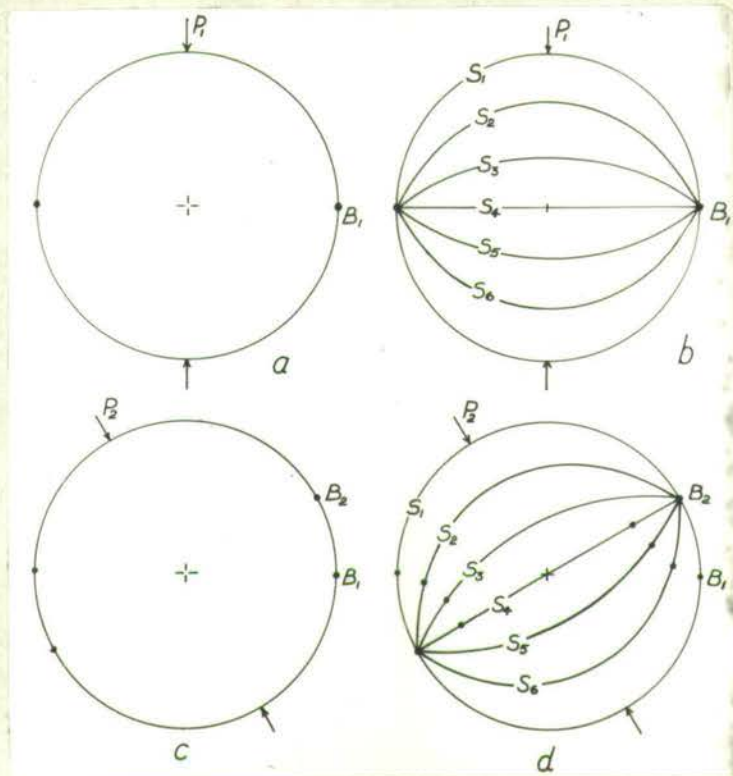


Figure 18. Structures produced by superposed biaxial strains (S-active flow).

Large folds usually are formed only by a first deformation of horizontal layers. Structures produced by a second strain generally take the form of small scale folds, mullions and lineations superposed on the limbs of the early-formed large folds.

I. Deformations by S - active flow superposed upon deformations by S - active flow

Some examples of these (for biaxial strains only) have been considered by Sander in his account of techniques of unrolling (Sander, 1948, pp. 170 to 184).

Some simplified general cases are as follows:

1. Biaxial strain followed by biaxial strain.
 2. Triaxial strain followed by biaxial strain.
 3. Biaxial strain followed by triaxial strain.
 4. Triaxial strain followed by triaxial strain.
1. Biaxial strain (\underline{P}_1) of \underline{S} produces either lineation (\underline{B} , in figure 18a) or flexural slip folds ($\underline{S}_1, \underline{S}_2, \underline{S}_3$ and so on, with axes \underline{B} , in figure 18b), depending on the scale of investigation. The lineation generally is a \underline{B} - lineation and the axes of folds invariably are \underline{B} - axes. The second biaxial strain (\underline{P}_2) oblique to \underline{P}_1 is expressed as/

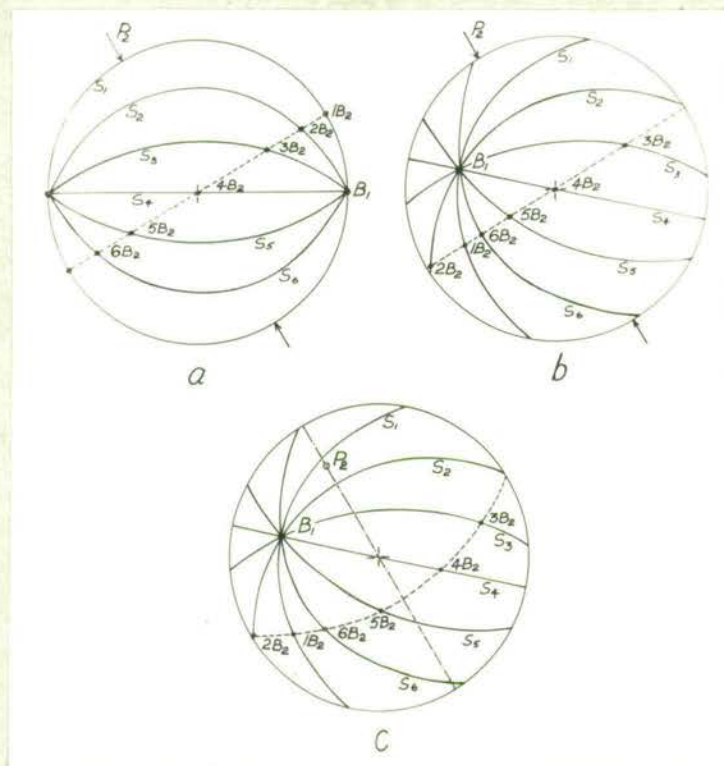


Figure 19. Structures produced by superposed biaxial strains (S-active flow).

as \underline{B} - structures on a small scale (\underline{B}_2). If \underline{S} still is planar after the first strain and carries \underline{B} , as a lineation, then \underline{B}_2 can be impressed on \underline{S} as a second lineation oblique to \underline{B}_1 , without changing the orientation of \underline{S} (figure 18c). If the second strain produces flexural slip folds in the previously planar \underline{S} then \underline{B}_1 is externally rotated about \underline{B}_2 so that on different positions of \underline{S} (\underline{S}_1 , \underline{S}_2 , \underline{S}_3 and so on in figure 18d) it lies on a small circle of the projection, centre \underline{B}_2 .

In the case where \underline{S} is folded about \underline{B}_1 , \underline{B}_2 is impressed as small scale structures with varying plunge upon the different attitudes of \underline{S} . These \underline{B}_2 - structures lie in a plane normal to \underline{P}_2 ($1\underline{B}_2$, $2\underline{B}_2$, $3\underline{B}_2$ and so on in figure 19a). If \underline{B}_1 plunges in a field of investigation before the second deformation, $1\underline{B}_2$, $2\underline{B}_2$, $3\underline{B}_2$ and so on, still lie in the same vertical plane intersecting the folded \underline{S} (figure 19b). If the second deformation is rotational owing to the action of a force-couple in a vertical plane, then \underline{P}_2 is no longer horizontal and the plane/

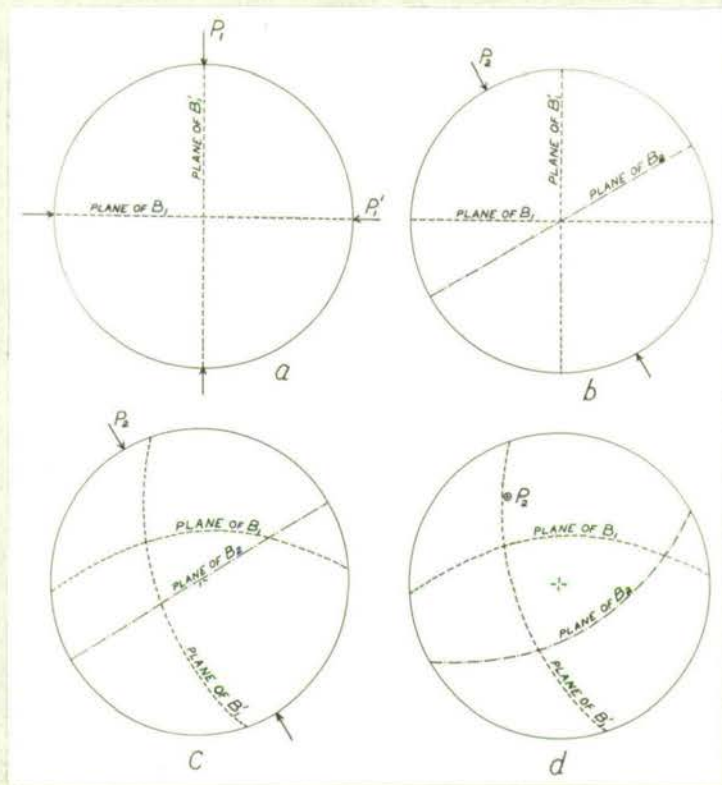


Figure 20. Structures produced by biaxial strain superposed on triaxial strain (S-active flow).

plane of \underline{B}_2 is correspondingly inclined (figure 19c).

2. The first triaxial strain is depicted by the two mutually perpendicular planes in figure 20a. The plane normal to \underline{P}_1 contains the \underline{B}_1 -axes; the plane normal to \underline{P}'_1 contains the \underline{B}'_1 -axes (see, also, figure 13).

Biaxial strain of the $\underline{B}_1 \perp \underline{B}'_1$ -structure produces \underline{B}_2 -structures lying in different orientations of \underline{S} in a plane normal to \underline{P}_2 (figure 20b). If the field is externally rotated after the first deformation, then the three great circles corresponding to planes of \underline{B} -structures intersect as shown in figure 20c. Likewise, if the second strain is rotational, the plane of \underline{B}_2 is inclined (figure 20d).

3. Folds in \underline{S} about \underline{B}_1 , produced by the first biaxial strain, have superposed upon them \underline{B}_2 -structures and \underline{B}'_2 -structures lying in two planes respectively normal to \underline{P}_2 and \underline{P}'_2 , the axes of greatest principal stress responsible for the second triaxial strain (figure 21a). If \underline{B}_1 plunges before the second deformation the geometry is as in figure 21b.

4. Superposed triaxial strains produce \underline{B} -structures lying in four planes (two oblique pairs of mutually perpendicular/

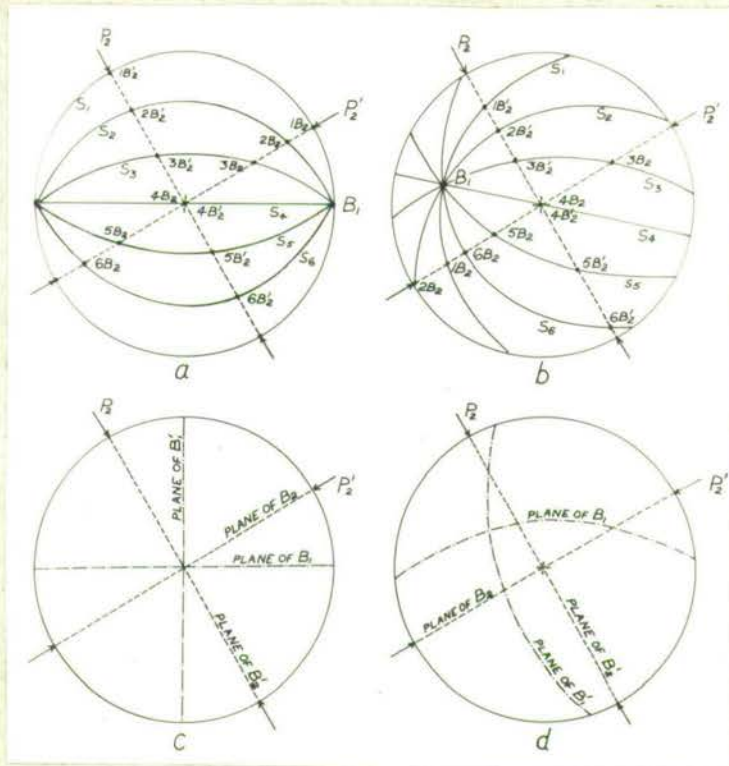


Figure 21. Structures produced by, a and b, triaxial strain superposed on biaxial strain, and, c and d, triaxial strain superposed on triaxial strain (S-active flow),

perpendicular planes) normal respectively to \underline{P}_1 , \underline{P}'_1 and \underline{P}_2 , \underline{P}'_2 (figure 21c). If external rotation occurs before the second deformation the geometry is as in figure 21d. \underline{S} can have any orientation and \underline{B} - axes almost any orientation; but the \underline{B} - axes fall into statistically planar sets of common origin.

These geometrical transformations are ideally simplified and it is doubtful if the more complex examples such as 3 and 4 (above) are clearly enough represented in naturally deformed rocks ever to be recognized with certainty. The four cases demonstrate the great complexity of structural geometry that can arise theoretically by superposition of relatively simple unrelated strains by \underline{S} - active flow. Lineations and small folds can be formed with any trend and plunge, and in sets with different geometry, on the limbs of large early-formed folds; early-formed folds can be bent and twisted by later strains in a manner which, on a small scale, appears to be completely irregular. In studying such structures the $\underline{\beta}$ - diagrams and the $\underline{\Pi}$ - diagram are of little or no use because they are/

are significant only for fields with statistical monoclinic symmetry; and, although some fields represented by the figures 19 to 21 would in natural examples be divisible into smaller fields with monoclinic symmetry, the variations in orientation and significance of B - axes and the identity of individual genetically related sets of B - axes can be demonstrated only on a very large scale. Generally, the B - axes can be separated into groups with common significance only on the basis of their orientation; but, if some of the B - structures are small folds, the attitude of the axial planes of folds can be helpful in determining to which group a particular axis belongs. The axial surface of each flexural slip fold tends to be normal to the P which formed it.

The symmetry of all the structures described is triclinic on some scales, but the symmetry is primary symmetry and not secondary symmetry. This is because on very small scales symmetry of fabric does agree with symmetry of strain. If the last strain has monoclinic symmetry/

symmetry then it produces, in a homogeneous field, monoclinic symmetry of fabric. The triclinic symmetry is an integration of small homogeneous fields inhomogeneous amongst themselves.

On most scales, the second strain is triclinic even where it corresponds on a large scale to an external biaxial strain with higher symmetry. An example is given by figure 21a which, on a very large scale, shows the structures produced by the superposition of triaxial strain on a biaxial strain. The diagram has one plane of symmetry (the plane of the diagram) so that the symmetry of fabric on a large scale is monoclinic. So, also is the symmetry of strain.

These \underline{S} - active deformations correspond on a large scale to symmetrical slip and restricted transport. On a small scale, slip can be asymmetrical (for planar orientations of \underline{S}). On the other hand, \underline{S} - active flow by asymmetrical slip on a large scale, can correspond to unrestricted transport. For this to be so, \underline{S} must remain statistically planar although it may become tilted by external rotation.

II./

II. Deformations by \underline{S} - passive flow superposed on deformations by \underline{S} - active flow.

There are two kinds of \underline{S} - passive flow theoretically possible on a large scale, namely, symmetrical slip and asymmetrical slip. \underline{S} - passive flow by symmetrical slip transforms \underline{S} in a complex fashion by internal rotations which vary according to the identity and orientation of the slip surfaces. All kinds of linear structures can be produced marking intersections slip surfaces with different altitudes of \underline{S} . The most important feature of fabrics produced in this fashion is a homogeneous orientation pattern of active structural components on a microscopic scale which does not have even the partially symmetrical relation to passive \underline{S} possessed by genetically related homogeneous imprints, as outlined above. The strain produced by \underline{S} - passive flow and symmetrical slip is orthorhombic on all scales whereas the fabrics produced by this strain when superposed on structures produced by \underline{S} - active flow have, in the general case, secondary triclinic symmetry on all scales. Whether strain by \underline{S} - passive flow is biaxial (\underline{P}_2) or/

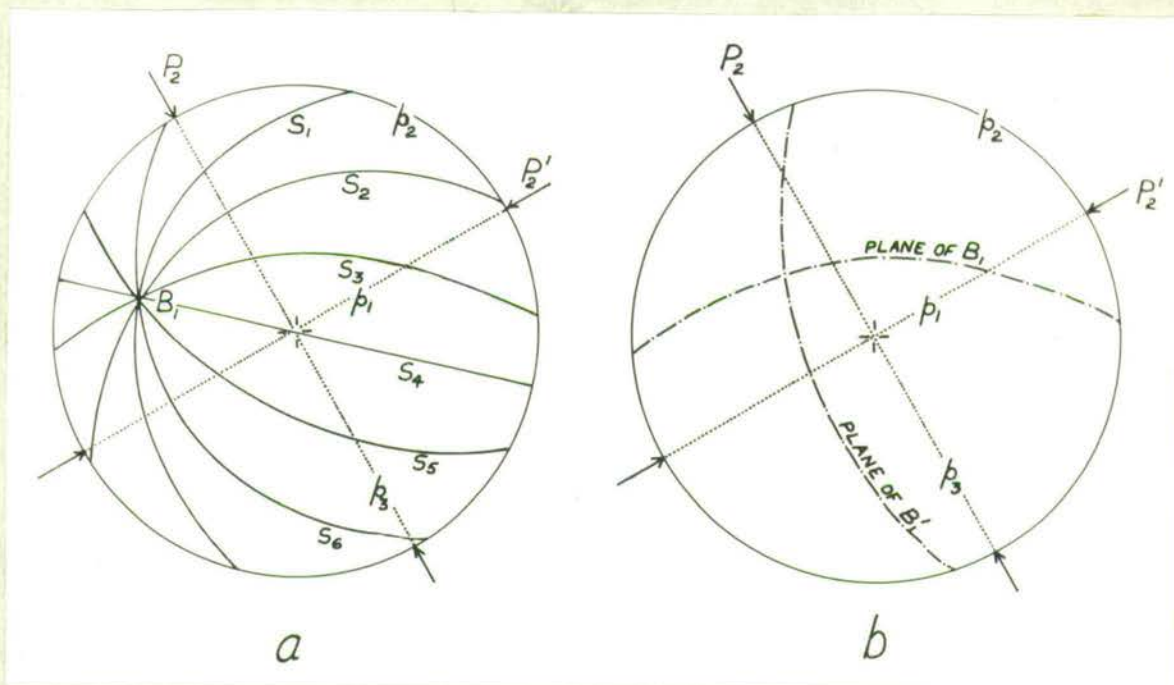


Figure 22. a. structures produced by triaxial strain (S-passive flow by symmetrical slip) superposed on biaxial strain (S-active flow).
 b. structures produced by triaxial strain (S-passive flow by symmetrical slip) superposed on triaxial strain (S-active flow).

or triaxial ($\underline{P}_2 \perp \underline{P}_2'$) the homogeneous imprint in active components has three mutually perpendicular planes of symmetry (\underline{P}_1 , \underline{P}_2 and \underline{P}_3). In figure 22a there are shown superposed upon a plunging cylindroidal fold produced in a first biaxial strain by \underline{S} - active flow and in figure 22b schematically superposed on $\underline{B}_1 \perp \underline{B}_1'$ -structures produced by triaxial strain. The only expression of \underline{P}_1 , \underline{P}_2 and \underline{P}_3 may be in active components on a microscopic scale but these planes of symmetry have constant orientation irrespective of the orientation of \underline{S} , \underline{B}_1 or \underline{B}_1' .

Most of the transformations of \underline{S} so far discussed correspond broadly to restricted transport: not all rotational strain corresponds to unrestricted transport. The last transformation to be considered, namely, \underline{S} - passive flow by asymmetrical slip on a single set of slip surfaces, belongs, on a large scale, in the category of unrestricted transport. Two orientations for the single set of slip surfaces (\underline{S}') are considered.

1. \underline{S}' is moderately dipping and intersects the horizontal parallel to the axis of slip (\underline{B} - axis). This corresponds/

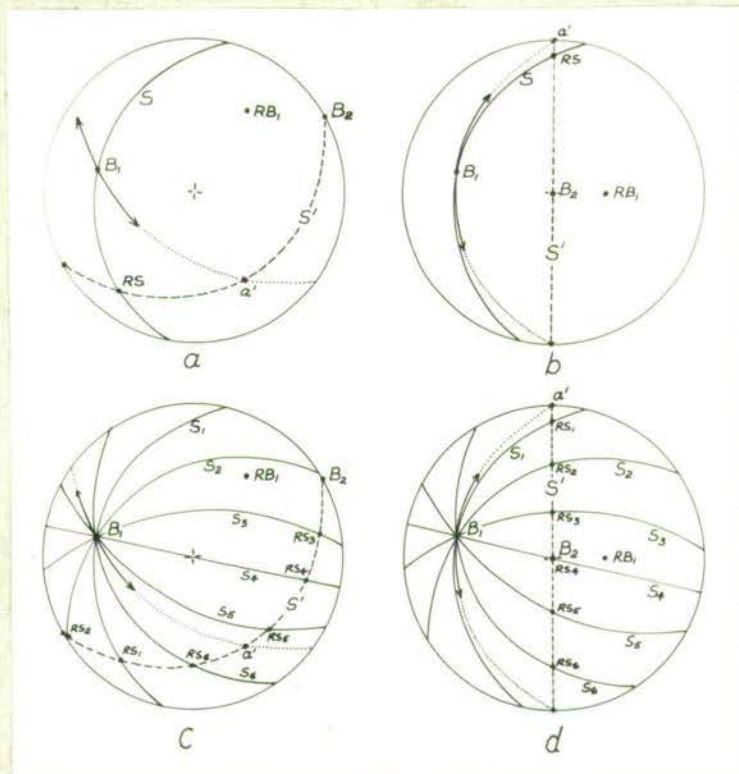


Figure 23. Structures produced by biaxial strain
 (S-passive flow by asymmetrical slip)
 superposed on biaxial strain (S-active flow).

corresponds to rotational strain about a horizontal axis. \underline{P} is either horizontal (a horizontal squeezing) or inclined (a force couple in a vertical plane).

2. \underline{S}' is vertical and the axis of slip is vertical. This corresponds to rotational strain about a vertical axis. \underline{P} is horizontal.

In a field which, after the first deformation, has a uniformly dipping \underline{S} with a \underline{B} - axis expressed as a lineation, \underline{S}' intersects and internally rotates \underline{S} in the manner shown in figures 23a and b. For case 1 above, the geometry is shown in figure 23a. \underline{RS} is the axis of internal rotation of \underline{S} , which, if the slip on \underline{S}' is non-affine, can become an axis of slip folding of \underline{S} . \underline{B}_1 is rotated about the axis \underline{RB}_1 (the normal to the plane containing \underline{B}_1 and \underline{a}' , the direction of slip in \underline{S}') in a sense decided by the sense of slip on \underline{S}' . Non-affine slip produces a bending of the axis \underline{B}_1 . The geometry for case 2, above, is shown in figure 23b.

Where \underline{S} is folded about \underline{B}_1 the geometry is more complex because each orientation of \underline{S} (\underline{S}_1 , \underline{S}_2 , \underline{S}_3 and so on in figures 23c and d) has its own axis of internal rotation/

rotation parallel to its intersection with \underline{S}' (\underline{RS}_1 , \underline{RS}_2 , \underline{RS}_3 and so on). These axes can be expressed either as lineations, or, if deformation is non-affine as axes of slip folds. The fold axis, \underline{B}_1 , behaves in the same fashion as a line, and is internally rotated in the same manner as the lineation (about \underline{RB}_1) in a sense decided by the sense of slip on \underline{S}' . \underline{B}_1 can be rotated only towards \underline{a}' ; for \underline{B}_1 to reach \underline{a}' , or for \underline{S} to become parallel to \underline{S}' by internal rotation, requires infinitely great deformation. The geometry for cases 1 and 2 is shown schematically, respectively in figures 23c and 23d.

These \underline{S} - passive strains by asymmetrical slip have monoclinic symmetry, but, for the general case, the resultant fabrics has secondary triclinic symmetry on all scales.

It was pointed out in the discussion of kinematic evolution in response to a single deformation that the mechanism of deformation, and thus the geometry and symmetry of fabric, can vary in different members of a uniformly strained compositionally heterogeneous body: \underline{S} - active flow may occur/

occur in one member, synchronously with S - passive flow in another, and so on. The same is true with respect to superposed deformations. The transformations of S described above are schematic and would be observed only under conditions of uniformity impossible in most bodies of naturally deformed rock. They are included here to show how complex fabrics with B - axis oriented in many directions can arise by superposition of strains. Most of the lineations produced by superposed deformations are B - lineations, whatever their orientation, and the axes of all flexural slip folds are B - axes; but some lineations and some slip folds formed by intersections of passive S with flow surfaces define axes which neither B - nor a - axes but have an intermediate orientation.

Finally, in this discussion of superposed deformations, it is necessary to outline the empirical argument used by Sander (1948, p. 180) to distinguish fabrics with triclinic symmetry resulting from triclinic strain from fabrics with triclinic symmetry resulting from a superposition of two unrelated strains. The more complex/

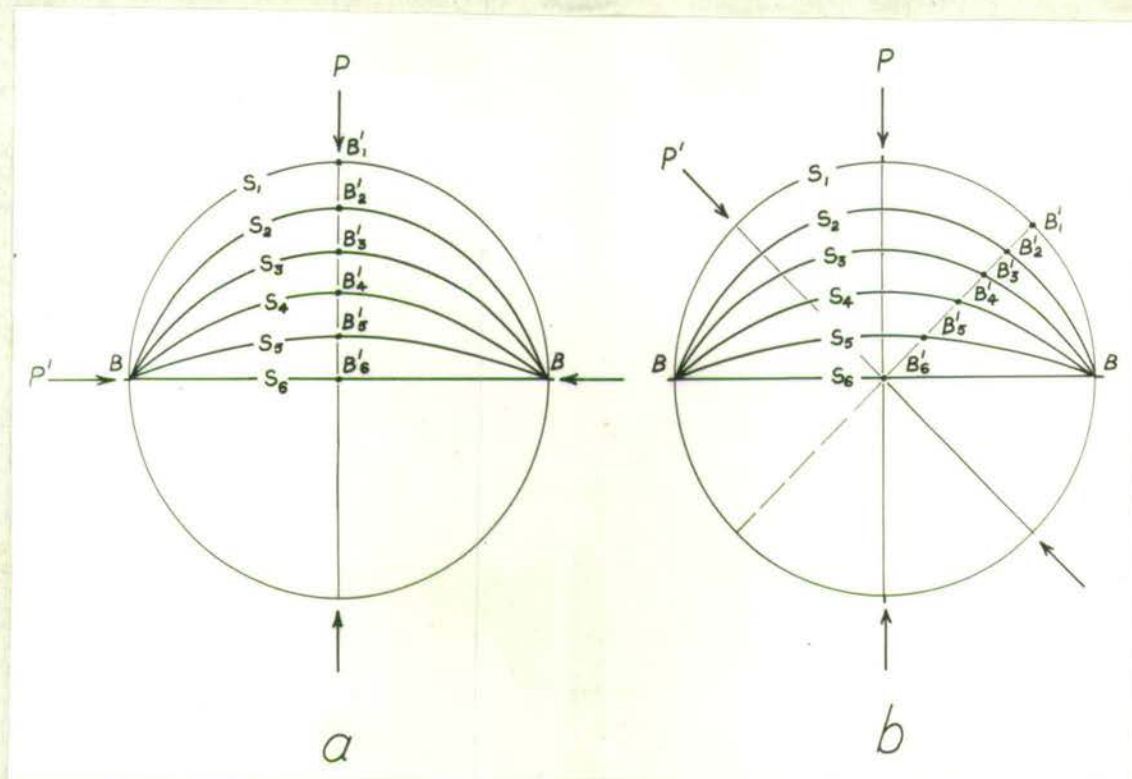


Figure 24. a. Triclinic strain ($\underline{B} \perp \underline{B}'$ -tectonics).
 b. Superposed biaxial strains
 ($\underline{B} \wedge \underline{B}'$ -tectonics).

complex examples of superposed deformations, such as superposed triaxial strains or a biaxial strain superposed on a triaxial strain have complex geometry, such as could be produced by no single strain. The case for which confusion most commonly arises is superposed biaxial strains by \underline{S} - active flow, which resembles triaxial strain by \underline{S} - active flow. Sander points out that, on a large scale, a triaxial strain (\underline{P} and \underline{P}' in figure 24a) produces \underline{B} - axes (respectively \underline{B} and \underline{B}') which are statistically mutually perpendicular; hence tectonites produced in this fashion are denoted as $\underline{B} \perp \underline{B}'$ - tectonites although, on a small scale, \underline{B} and \underline{B}' may not be mutually perpendicular. For the general case of superposed biaxial strains (\underline{P} and \underline{P}' in figure 24b) the angle between \underline{B} & \underline{B}' is statistically other than a right angle; hence tectonites produced in this fashion are denoted as $\underline{B} \wedge \underline{B}'$ - tectonites. Where \underline{P} and \underline{P}' are mutually perpendicular and represent unrelated biaxial strains, the structures produced are indistinguishable from $\underline{B} \perp \underline{B}'$ - structures, unless other criteria for genetically separating \underline{P} and \underline{P}' can be found.

13.

SUMMARY OF CONCLUSIONS

In this paper an attempt is made to present a unified/

unified if greatly simplified view of the structures produced by flow in deformed rocks, and to show how the geometry and symmetry of these structures can be related to the geometry and symmetry of strain. The following conclusions emerge which are important from the viewpoint of statistical structural analysis of large bodies of deformed rock:

1. The geometry and symmetry of patterns of preferred orientation of mineral grains produced by a given strain depend to a large extent upon whether the grains have participated actively (by intragranular strain) or passively (by intergranular strain) in deformation.

2. In large bodies of layered rock, deformation produces flow which, for a given member, is broadly of one of two kinds. If the layering is S, then flow is either S - active or S - passive. In the first, S is the only or the most important slip surface in the fabric, in the second, S is not a slip surface, and other slip surfaces are present. These two terms denote families of phenomena which can, in the view of the writer, be justifiably separated in large bodies of rock deformed by flow.

3./

3. If a large enough field is considered, deformation by either \underline{S} - active or \underline{S} - passive flow can achieve statistical homogeneity of external strain. Also, because a strain which is inhomogeneous on a small scale can be statistically homogeneous on a large scale a fabric with monoclinic or triclinic symmetry on a small scale can have orthorhombic symmetry on a large scale.

4. \underline{S} - active flow may pass, with progressive deformation, into \underline{S} - passive flow, in certain rocks. Because changes in mechanisms of deformation can appear with progressive deformation, a given system of stresses can produce fabrics which evolve kinematically and structurally through stages with different geometry and symmetry as deformation proceeds. Adjoining members of one strained body differing in composition, can deform synchronously by different mechanisms of internal strain. Deformation generally begins by \underline{S} - active flow until \underline{S} is "neutralized" by folding. In certain members \underline{S} retains its identity but becomes structurally passive, in others it is transposed into a new \underline{S} . There is a tendency for strain to become homogeneous on smaller and smaller scales as deformation proceeds. Where deformation becomes statistically homogeneous/

homogeneous on the granular scale, active structural components carry a homogeneous imprint throughout a field of statistically affine deformation.

5. Symmetry of fabric is of two kinds: primary symmetry and secondary symmetry. The first is defined by structurally active components and elements, and agrees with symmetry of strain in a given field; the second is defined by structurally passive components and elements, and does not necessarily agree with symmetry of strain in a given field. These two kinds of symmetry can occur on any scale. The principle of symmetry holds without exception only for primary symmetry.

6. In fields on all scales, fabrics produced by superposed deformations have, as a general rule, triclinic symmetry. Where only S - active flow is involved, the symmetry is always primary: where S - passive flow is involved the symmetry is secondary.

14.

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THE
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II. APPLICATIONS of STRUCTURAL ANALYSIS to
REGIONAL STUDIES.

II. 7. Tectonic Features of the Hecla Hook Formation
to the South of St.Jonsfjord,
Vestspitsbergen.

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Tectonic Features of the Hecla Hook Formation to the South of St. Jonsfjord, Vestspitsbergen

By L. E. WEISS

ABSTRACT

A structural study of rocks of the Hecla Hook formation in the area of Forlandsundet of Vestspitsbergen reveals the presence of two B -axes. The earlier (B_1) trends roughly east-west and affects only the Hecla Hook formation; the later axis (B_2) trends roughly north-south, and affects also rocks of Carboniferous age. It is suggested that B_1 is the main "Caledonian" axis in this area, and that B_2 and the roughly north-south "grain" of the rocks concerned are Lower Tertiary phenomena.

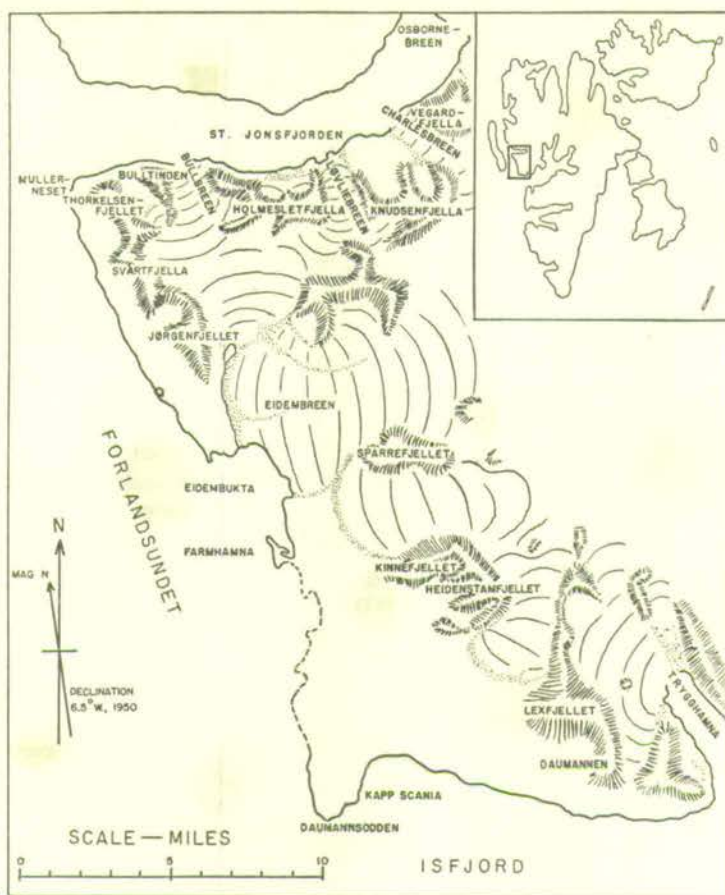
INTRODUCTION

IN the summer of 1948 the writer visited Vestspitsbergen as a member of a small expedition from the Department of Geology at the University of Birmingham. This expedition, led by M. F. W. Holland, investigated the geology of the area lying between Isfjord and Eidembreen (Text-fig. 1). During a traverse from Trygghamna to Daumannsodden one member (B. H. Baker) discovered a fossil-bearing horizon within the supposed Hecla Hook rocks at Kapp Scania. This discovery was made during the last phase of the work, and no time was then available for detailed mapping of the area. The fossils, mainly corals and brachiopods, are very poorly preserved, as the rocks in which they occur have been strongly deformed. It was thus tentatively assumed at the time that the horizon was part of the Hecla Hook succession and that the fossils were probably of Lower Palaeozoic age. Subsequently A. Orvin and O. Holtedahl, of the Norsk Polar-institut, in Oslo, identified the corals as Carboniferous forms, thus raising a number of tectonic problems necessitating further field work.

In the summer of 1951 the writer accompanied a second expedition from the University of Birmingham, led by E. R. Hitchcock, to the area lying between Eidembreen and St. Jonsfjord (Text-fig. 1). Kapp Scania was visited in the same year by the joint Oxford and Cambridge Universities expedition to Nordaustlandet, and an extensive collection of fossils were made at the original locality. It is from this collection that Forbes obtained the material which he described in a letter to the *Geological Magazine* (lxxxix, 1952, p. 303).

The writer made two geological traverses in rocks of the Hecla Hook formation from a base near Müllerneset, first along the southern shore of St. Jonsfjord to the Charlesbreen, and secondly southward along the coast of Forlandsundet to the lateral moraines of Eidembreen. During the second of these traverses the northward prolongation of the

Carboniferous rocks of Kapp Scania was found in the coastal mountains, where they form a narrow outcrop striking approximately north-north-west and bounded upon both sides by rocks of the Hecla Hook formation. The outcrop stretches from Müllerneset southward to



TEXT-FIG. 1.—Sketch-map of the Isfjord—St. Jonsfjorden region of Vestspitsbergen, showing its location on inset outline map of Svalbard.

Eidembukta, where it vanishes into the sea to reappear somewhere between the south side of Eidembreen and Daumannsodden.

The purpose of this preliminary paper is briefly to record some observations made upon the detailed tectonics of the Hecla Hook formation in this area. The newly discovered Carboniferous rocks

enter closely into the structure of Forlandsundet coast, and no discussion of the tectonics of the Hecla Hook formation would be complete without also considering these. It is hoped at some future date to report in greater detail (in collaboration with B. H. Baker) the petrography and structural petrology of the Hecla Hook formation between St. Jonsfjord and Isfjord. Another field season is required before the publication of a geological map and accompanying report will become possible.

1. THE HECLA HOOK FORMATION BETWEEN ST. JONSFJORDEN AND EIDEMBREEN

Metamorphic rocks of the Hecla Hook formation occupy most of the area lying between St. Jonsfjorden and Eidembreen. To the east they are unconformably overlain by Culm rocks of Carboniferous age along a line running between Vegardfjella, in the north, and Trygghamna, in the south. As elsewhere in Vestspitsbergen, the Hecla Hook rocks are products of metamorphism of low to medium intensity and comprise a mixed series of slates, phyllites, quartzites, mica schists, and calcite or dolomite marbles, associated with basic intrusives. For the purpose of this paper the Hecla Hook formation in the area has been divided into two broad structural and lithological units, differing in geographical distribution and possibly age as well.

(i) *The eastern series* consists of those rocks lying to the east of the newly discovered Carboniferous outcrop. It is exposed along the southern shore of St. Jonsfjorden and is unconformably overlain by the main Carboniferous formation near the ice cliffs of Osbornebreen (Holtedahl, 1912, pp. 67-70).

(ii) *The western series* consists of those rocks lying to the west of the Carboniferous outcrop. It forms the coast of Forlandsundet from Müllerneset to the promontory on the north side of Eidembukta (Text-fig. 1).

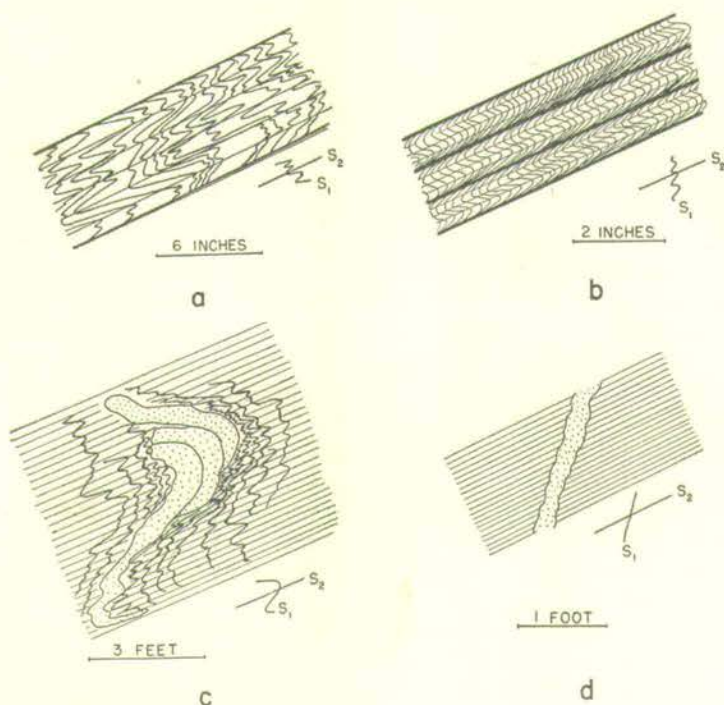
The main folding and metamorphism of the Hecla Hook formation is known to be of pre-Devonian age (Orvin, 1940, pp. 11-15), but it seems likely that these rocks should also show some trace of the post-Carboniferous deformation which has strongly affected the Carboniferous rocks of the Foreland Sound. It seems important that care be taken to separate the effects of the two deformations. With this aim in view field work in the summer of 1951 was directed towards an accumulation of as many structural data as possible. Altogether over 1,000 measurements of the strike and dip of *s*-planes and the trend and plunge of fold axes and lineations were made. Work was confined to the regions where surface creep was at a minimum, and the traverses were conducted largely upon the raised wave-cut marine platform and in the excellent cliff sections. The data so obtained have been plotted

on a Schmidt-Lambert equal-area projection and analysed in accordance with the normal procedure in structural petrology.

(i) *The Eastern Series*

Foliation.

With the exception of the massive quartzite bodies which occur in



TEXT-FIG. 2.—Profiles of folds about the axis B_1 in the eastern series of the Hecla Hook formation.

(a) Folding in a calcareous semi-pelite. S_2 is parallel to the axial-planes of the folds affecting S_1 . It pervades the whole rock but tends to be concentrated in movement planes spaced a few inches apart.

(b) Folding in a more competent calcareous schist. S_2 is concentrated in definite movement planes and arises by transposition of S_1 .

(c) Fold in pelitic schist to the west of Mount Bull. S_1 is represented by the sigmoidal psammitic body.

(d) Semi-pelitic schist showing complete obliteration of S_1 in the pelitic members. The discordant rib of quartzite with incipient boudinage is all that remains of S_1 .

the eastern part of Holmesletfjella and in Gunnar Knudsenfjella, most of the rocks of the eastern series show two megascopic s -planes.

Sedimentary bedding (S_1) is preserved in the slaty and phyllitic rocks as highly contorted and partially obliterated colour banding or as lenses and streaks of obdurate psammite. It has been intensely folded and sheared, with the production of a second megascopic foliation plane (S_2) roughly parallel to the axial-planes of the folds. This is developed mainly in the pelitic, semi-pelitic, and calcareous rocks. The massive quartzites lack both foliation and bedding. Text-figs. 2 (a) to (d) are profiles, that is, sections drawn normal to fold axes (see D. B. McIntyre, 1950, p. 331), showing the mutual relationship of S_1 and S_2 in different exposures.

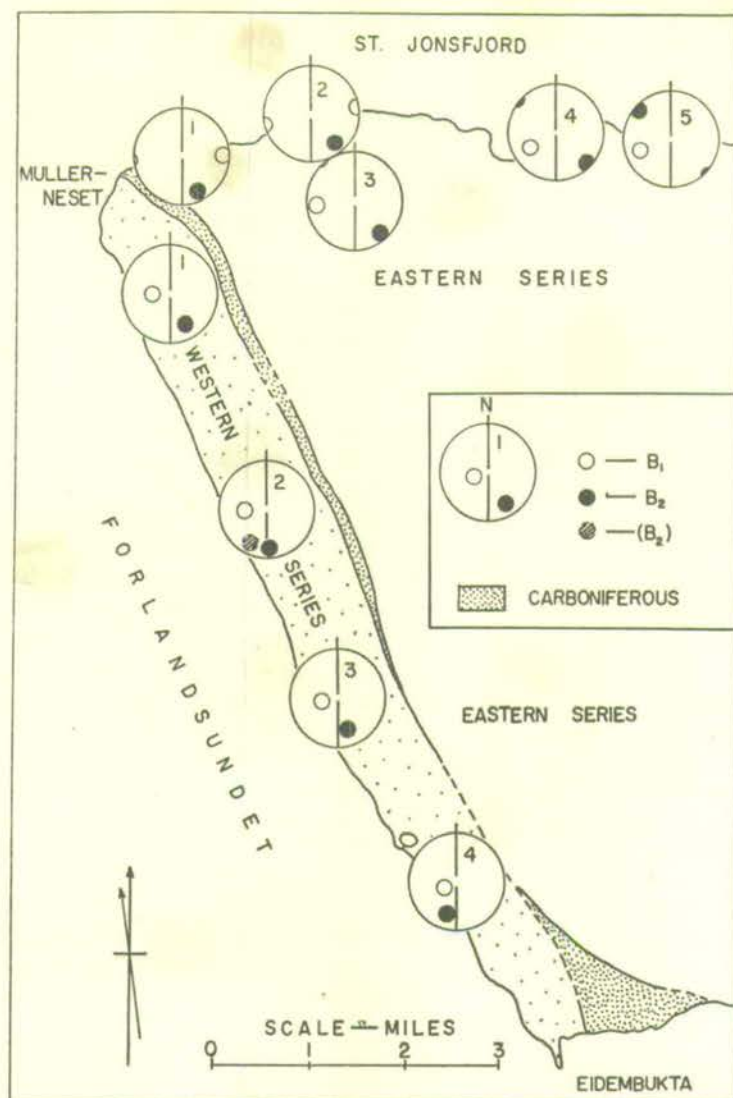
Within the rocks forming the southern shore of St. Jonsfjord, at least as far as Løvliebreen, the most pronounced megascopic s -plane is in many cases S_2 . The traverse made along this shore has shown the foliation of the eastern Hecla Hook formation to be disposed in a broad, open, asymmetrical synclinalorium about an axis trending roughly north-north-west and plunging gently to the south. The trough-line of this fold reaches the coast between Thorkelsenfjellet and Bulltinden (Text-fig. 1), and the fold is probably the northward prolongation of a similar fold mapped to the south of Daumannen by B. H. Baker, and in Heidenstamfjellet and Kinnéfjellet by the writer in 1948. In these areas the fold axis has the same trend, but the plunge is gently to the north. It is possible to erect stratigraphical units in the rocks forming this syncline, but as the foliation involved is sometimes S_2 instead of the original sedimentary layering S_1 , the units so erected may possibly have little value for correlation with stratigraphical units of the Hecla Hook formation in other parts of Vestspitsbergen. Only thick competent horizons such as the massive quartzites in the east and the even more massive dolomite marbles in the west of the area are likely to have retained an original stratigraphical continuity.

Folding and Lineation.

Two intersecting fold axes can be observed in many exposures within the eastern series, but there is a considerable variation of trend and plunge of both.

(a) There is a more or less east-west axis of penetrative folding on a small scale, affecting the bedding foliation S_1 as described above. The symmetry of folding is monoclinic (Text-fig. 2a-d), and the corresponding lineation parallel to the fold axes and normal to the single symmetry plane of the folded fabric is a b (B)-lineation which is designated B_1 .

(b) There is an axis of major folding trending between north-east and north-west, horizontal or plunging gently to the south. This is the



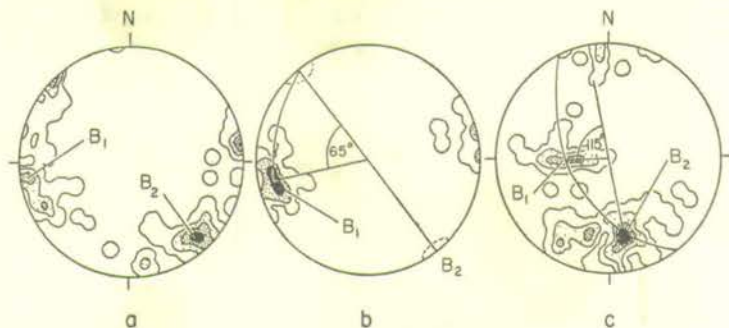
TEXT-FIG. 3.—Sub-areas of homogeneity for the eastern and western series of the Hecla Hook formation. The *B*-maxima are shown diagrammatically as circles which correspond approximately with a concentration of 20 per cent per 1 per cent area.

axis of the major syncline in the eastern series mentioned above. An accompanying lineation may be observed in some of the folded rocks. A study of the megascopic features of the folds about this axis has shown that the fabric has monoclinic symmetry with the plane of symmetry normal to the fold axis. This axis is also a B -axis and the accompanying lineation will be referred to as B_2 .

There are thus in this area traces of at least two periods of folding which have affected the eastern series of the Hecla Hook formation. Both of the fold axes are paralleled by lineations, and both are true B -axes (they are normal to the deformation planes determined by a study of megascopic structures, and to the corresponding planes of symmetry). Locally either of the two B -axes may be dominant, depending upon the relative strengths of the two deformations. In places one axis may be developed completely to exclusion of the other, but more generally traces of both may be seen in any one exposure. In order to demonstrate the distinct identity of the two B -axes graphically the poles of lineations and fold axes at various exposures have been plotted upon equal-area projections. As mentioned above, the eastern area is not tectonically homogeneous, due probably to local irregular tiltings and adjustments caused by the late Tertiary block faulting movements which have been operative in the area of Forlandsundet (A. K. Orvin, 1940, pp. 49-54), and a limited area only will be considered. The region between Müllerneset and Holmesletbreen has been divided into five sub-areas, and the B -axes measured in the field have been plotted for each area. The diagrams so obtained are shown geographically oriented in Text-fig. 3. Individual sub-areas are not completely homogeneous, but the two maxima corresponding to B_1 and B_2 can be separated and identified with little difficulty. Text-fig. 4a shows the combined data of the five diagrams for the sub-areas plotted collectively with common geographical co-ordinates. The two maxima corresponding to B_1 and B_2 are still readily separable, but they are less distinct than in the diagrams for the individual sub-areas. From the field evidence alone it is obvious that B_1 is the earlier axis; B_2 is the axis about which the foliation S_2 is folded, whereas S_2 itself is a direct result of the folding and shearing about B_1 . Concentration of earlier (B_1) axes is intensified if the individual B_2 -axes of the five sub-areas are rotated to mutual parallelism as in Text-fig. 4b. Such a procedure is only an artificial means of regaining homogeneity, for the rotations have been carried out arbitrarily about a vertical axis; but as the angles involved are small it is a useful way of demonstrating the relative constancy of the angle between B_1 and B_2 , regardless of their trend and plunge in individual exposures. The average angle between the two axes in the north-west quadrant is about 65° (Text-fig. 4b).

(ii) *The Western Series**Foliation.*

Unlike the eastern series, the western series of the Hecla Hook formation usually shows only one marked foliation plane and this is more pronounced than those of the eastern series. Compositional variation in the rock types, which commonly is rapid, invariably parallels the



TEXT-FIG. 4.—(a) and (b) *B*-axes in the eastern series. 109 axes; contours 2–6–10–14 per cent per 1 per cent area.

(c) *B*-axes in the western series. 70 axes; contours 1–4–8–10 per cent per 1 per cent area.

foliation plane. The horizons of massive white quartzite which are common along the coast of Forlandsundet lie along the foliation plane in a perfectly conformable fashion. For this reason the foliation is interpreted as being equivalent to S_1 in the eastern series, as well as to S_2 . In the western series the highly competent nature of most of the rocks involved seems to have caused the S_2 foliation to develop parallel to the pre-existent S_1 bedding planes, as it has in the competent horizons in the eastern series. Throughout the whole outcrop of the western series the foliation, which will be referred to as S_{1-2} , has a generally north to south strike except for local variations. The dip of the foliation plane is usually 60° – 70° due west, but it may also be steeply to the east, more particularly in a narrow area immediately adjacent to the junction with the Carboniferous rocks. The consistently steep dip of the foliation and the regularity of its strike contrast strongly with the dominantly shallow dip and variable strike of S_1 and S_2 in the eastern series.

In some incompetent beds a second foliation is locally developed parallel to the axial-planes of folds the axes of which plunge gently to the south. This foliation (S_3) is generally conformable to the regional foliation plane, in striking between north-north-west and north, and dipping steeply to the west. It is thus likely that the regional foliation of the western series (S_{1-2}), in addition, owes some of its prominence

to the movements which have produced S_3 in the more incompetent beds.

Folding and Lineation.

Like the eastern series, the western series has been affected by at least two systems of folding about axes with markedly different orientations :—

(a) An early axis, intermittently and faintly developed, and plunging steeply to the west or west-south-west.

(b) A later much more pronounced axis trending approximately north-south and plunging gently to the south.

The second axis agrees closely with the dominantly north-north-west trend of the B_2 -axis in the eastern series, and for this reason the two are correlated. In the western series the effects of the B_2 -axis are very strong ; it is paralleled by a pronounced lineation which is visible in almost all exposures. B_2 has become an axis of extension as well as one of folding, as is shown by pebbles in a conglomeratic layer which are strongly elongated parallel to B_2 . Locally, in very incompetent schist horizons, an axial-plane foliation (S_3) has developed parallel to the axial-planes of folds about B_2 .

Along the Foreland Sound coast the rocks have all assumed a steep and regular westward dip, and the lineation parallel to B_2 is intense. The earlier of the two axes, which is most easily observed in this area, plunges approximately down dip and is weaker than the B_2 -axis. This axis is correlated with the B_1 -axis of the eastern series with which it agrees in trend. It is marked by only weak lineation and, with the exception of rare, large, open folds, by folding only on a small scale.

In order to bring out regularity in structure of the western area it, too, has been divided into a number of sub-areas. Text-fig. 3 (lower portion) shows the four sub-areas with geographically oriented equal area projections of the corresponding B -axes ; at least two areas of B -axis concentration can be distinguished in each projection, and in that for sub-area 2 there is also a third. The data for the four sub-areas are combined as a collective diagram in Text-fig. 4c. The sub-maximum associated with the main B_2 concentration most probably represents a local variation of the B_2 -axis, as the angle between the two maxima is small.

In general the structure of the western series agrees closely with that of the eastern series. In both there is evidence of an earlier B -axis trending roughly east-west, and a later B -axis trending approximately north-south. The average angle between the statistical maxima for B_1 and B_2 measured in the north-west quadrant in both cases is 65° in

the eastern series but is 115° in the western series. Other weak axes may be developed locally, but at the present time insufficient information is available to systematize the occurrence of these.

2. THE CARBONIFEROUS ROCKS OF THE FORLANDSUNDET

General Description.

Since the writer has had no opportunity to make a study of the original outcrop of Carboniferous rocks at Kapp Scania, observations in this paper will be confined to the features of those Carboniferous strata exposed between Eidembreen and Müllerneset. The greatest width of their outcrop is attained near Eidembreen (Text-fig. 3), where it is wedge-shaped and about three-quarters of a mile wide at the coast. To the north the outcrop narrows until, to the west of Jørgenfjellet, it vanishes for a distance of $1\frac{1}{4}$ miles. The exposure is poor in this area and it is possible that the eastern and western series of the Hecla Hook formation everywhere are separated by a small thickness of Carboniferous rocks. Near the southern spur of Svartfjella the Carboniferous rocks appear again as a narrow white quartzite exposed in the gorge of a river, and the outcrop widens rapidly as it climbs into the mountains. It maintains a constant and considerable width throughout the length of Svartfjella and Thorkelsenfjellet and thins again slightly as it falls to the coastal plane before vanishing into the sea at Müllerneset (Text-fig. 3). The series contains massive white, buff, and red quartzites, grey limestones, and silicified limestones containing many jasperitic fossils. One horizon of calcareous tufa occurs in the succession just to the north of Eidembreen. The stratigraphy of these rocks is beyond the scope of this work, but on stratigraphical grounds alone the rocks appear to represent a large part of the Carboniferous succession, ranging from the centre of the Middle Carboniferous formation to somewhere in the Upper Carboniferous *Cyathophyllum* limestone (Holtedahl, 1912, pp. 1–34).

Tectonics.

Just to the west of Eidembreen, in a deep river gorge, the Carboniferous rocks are in contact with the Hecla Hook formation along a steeply dipping fault with a wide zone of brecciation. At the junction the foliation in the eastern series strikes south-east and dips at 40° eastward, whereas the bedding in the Carboniferous rocks (massive grey limestones and quartzites in this area) strikes approximately east-west. The strike of the fault parallels that of the foliation in the eastern series and so transgresses that of the bedding in the Carboniferous rocks. The junction of the Carboniferous rocks with the western series is nowhere accessibly exposed, but reasons will presently

be put forward for believing that this is of a quite different nature. At Müllerneset both junctions are well exposed in the cliff section, but as no boat was available for close examination of the cliffs, all that could be observed was a marked discordance of strike and dip between the foliation in the eastern series and the planar structure of the Carboniferous rocks at what is evidently a steeply faulted junction.

As contrasted with the relatively highly metamorphic Hecla Hook formation, the Carboniferous rocks of Forlandsundet are unmetamorphosed. At other localities in Vestspitsbergen the same is true, and Carboniferous rocks can be seen in a number of places resting unconformably upon metamorphic rocks of the Hecla Hook formation. In the area of Forlandsundet the Carboniferous rocks, though unmetamorphosed, are strongly deformed. In general intensity of deformation increases from the south towards the north, and at Müllerneset green phyllitic rocks with newly crystallized chlorite have formed locally from the mudstone layers within the limestones. Even in the vicinity of Eidembreen the Carboniferous rocks are strongly folded with the production of an axial-plane cleavage (S_a), in the incompetent layers, which has in many cases obliterated the original bedding (S_c). The intensity of the axial-plane cleavage increases towards the north, and fold axes with a gentle southward plunge are more commonly observed. At Müllerneset the only visible planar structure within the Carboniferous rocks is the axial-plane foliation (S_a) which conforms closely in dip and strike with the contact between the Carboniferous and the western series and with the foliation (S_{1-2}) within the western series. All fossils within the Carboniferous rocks have been destroyed by the strong deformation, and the green phyllites which were once mudstones now somewhat resemble the dark green phyllitic schists of the Hecla Hook formation with which they are in contact. The contact between the Carboniferous rocks and the western series thus differs greatly from the transgressive, obviously faulted, contact with the eastern series.

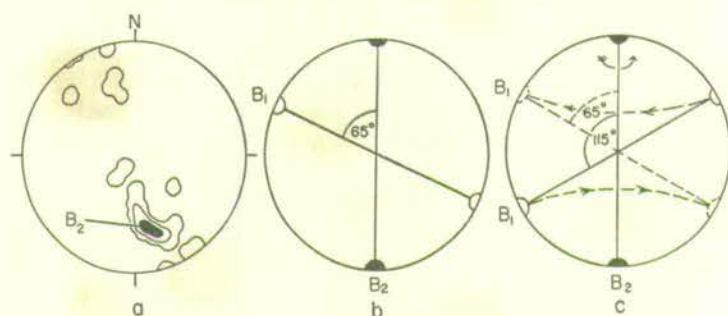
Fold axes in the Carboniferous rocks agree closely in trend and plunge with the north-south axes in the western series of the Hecla Hook formation (B_2). Towards Müllerneset a lineation is developed in the Carboniferous rocks which marks the intersection of the original bedding (S_c) with the axial-plane foliation (S_a). This, too, is a B -lineation. Text-fig. 5a is an equal area projection of fold axes and lineations measured within the Carboniferous rocks. The statistical maximum in this diagram corresponds closely in position with the B_2 maximum for the western series shown in Text-fig. 4c, and so the two are equated. Of the B_1 -axis no trace could be found within the Carboniferous rocks; it appears to be confined to and characteristic of the Hecla Hook series.

3. TECTONIC SYNTHESIS

Deformation in the region here described has occurred about two main B -axes.

(a) An earlier axis B_1 with west-north-west to west-south-west trend, recognizable in both the eastern and western series of the Hecla Hook formation, but not in the Carboniferous rocks. It is thus peculiar to and characteristic of the Hecla Hook formation.

(b) A later axis B_2 trending between north-east and north-west and recognizable in the Carboniferous rocks as well as in both the eastern and western series of the Hecla Hook formation.



TEXT-FIG. 5.—(a) B -axes in the Carboniferous series of Forlandsundet. 20 axes; contours 5–15–25 per cent per 1 per cent area.
(b) B -axes in the eastern series (diagrammatic).
(c) Inversion of the western series about B_2 , with respect to the eastern series.

Inversion of the steeply westward dipping foliation of the western series is strongly suggested by the angular relations of B_1 and B_2 , as measured in the north-west quadrant— 65° in the eastern series and the supplementary angle 115° in the western series. Since it is the trend of B_1 that is affected by the inversion it follows that the axis of inversion could well be B_2 ; B_2 is an axis of near-isoclinal folding in both the western and Carboniferous series. A diagrammatic sketch of the relations between the two B -axis maxima with respect to the inversion is given in Text-fig. 5b-c.

In both the western series and the Carboniferous rocks of the Foreland Sound area the B_2 -axis is strongly developed, folding about B_2 is nearly isoclinal, and an axial-plane foliation S_3 is developed locally. In rocks of the eastern series, on the other hand, B_2 is relatively weak, and folds about this axis are open and symmetrical or slightly over-turned from the west towards the east. This contrast in intensity of deformation, considered in conjunction with the strongly faulted contact between the Carboniferous rocks and the eastern series,

suggests that the coastal zone of strong movement about B_2 and the terrains occupied by the eastern series represent different tectonic horizons with respect to the movements about B_2 . The table below gives a diagrammatic resumé of the tectonic histories of the three formations. Suggested ages for the various structural features are given in the first column.

Age	Western Series	Carboniferous	Eastern Series
Lower Tertiary	Near-isoclinal folding of S_{1-2} about an axis trending between N.N.W. and N.N.E. (B_2). Axial-plane foliation (S_2) formed in incompetent beds.	Near-isoclinal folding of S_0 about an axis trending N.N.W. (B_1). Axial-plane foliation (S_2) developed in incompetent beds.	Moderately strong folding of S_1 and S_2 about an axis trending between N.W. and N.N.W. (B_2).
Carboniferous		Formation of original bedding (S_0).	
Upper Silurian			
Caledonides (Upper Ordovician-Lower Silurian) ?	Moderate folding of S_1 about an axis trending between W. and W.S.W. (B_1), with the formation of a "bedding" foliation (S_{1-2}) and metamorphism of the whole series.		Intense folding of S_1 about an axis trending between W. and W.S.W. (B_1). Axial-plane foliation (S_1) formed in incompetent beds and metamorphism of the whole series.
Upper Ordovician ?			
Cambro-Ordovician	Formation of original bedding (S_1).		Formation of original bedding (S_1).

4. ACKNOWLEDGMENTS

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II. 8. Structural Analysis of the Basement System
at Turoka, Kenya.

STRUCTURAL ANALYSIS OF THE BASEMENT SYSTEM

AT TUROKA, KENYA

by L. E. WEISS

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ABSTRACT

The principles and procedure of structural analysis of use in a reconnaissance survey are outlined, and more detailed procedure is used in the investigation of 40 square miles of Basement System at Turoka, Kenya. The rocks of this area are found to be structurally homogeneous with respect to a E-axis trending north 62° east and plunging at 20° . This geometry contrasts with that suggested by the Survey for an adjoining area, which assumes the presence of a horizontal fold axis parallel to the regional strike of foliation. Tectonic profiles are constructed; and on the basis of these, and the results of statistical analysis on macroscopic, megascopic and microscopic scale, a broad kinematic and dynamic interpretation of the structural geometry is attempted. It is suggested that initially horizontal layers were subjected to a prolonged phase of orogenic deformation by flow, which passed from a horizontal squeezing or shearing to a vertical flattening. The phase of flow was followed by a tilting of the E-axis so formed about an axis (E') which, on account of its orientation normal to E, is thought to be genetically related to E. The rotation about E' may denote a late element of triaxial strain in a deformation previously biaxial. Evidence /

Evidence is presented suggesting that the area of structural homogeneity can be extended over large adjoining areas.

FOREWORD

As the Geological Survey of Kenya proceeds with its current programme of surveying, which involves the geological mapping of the whole country on the scale of 1:125,000 at the rate of one quarter of a degree sheet per geologist per annum, so it is to be expected that problems of geological importance will be discovered at a far greater rate than they can be solved by the geologists of the Survey. This has proved especially true during the mapping of the substructure of ancient gneisses - the Basement System - upon which the younger geology of Kenya is built. The degree of structural complexity exhibited by this formation in many of its outcrops can only baffle the geologist whose main concern is the preparation in a limited period of time of a reconnaissance geological map on a small scale.

In order to examine problems lying outside the scope of reconnaissance geologists, the Colonial Survey, from time to time, encourages geologists with specialized knowledge of a particular field to investigate the geology of areas of key importance in greater detail than is possible for geologists concerned with a primary survey. In this fashion information may be obtained which could influence a particular programme of surveying or development.

This /

This paper is the outcome of one such detailed investigation involving two months of field work in the Basement System of Kenya during the summer of 1955. The purpose of the investigation was to apply to the rocks of the Basement System some of the techniques of statistical analysis of structural geometry which are being used to assist in an understanding of the evolution and significance of complex structures in other parts of the world.

The investigation was made under the auspices of the Colonial Development and Welfare Fund, the Department of Mines and Geology in Nairobi and the University of Edinburgh. The writer wishes to record his indebtedness to these three institutions and also to Professor A. Holmes of the University of Edinburgh, and to Dr W. Pulfrey and Mr P. Joubert of the Department of Mines and Geology who gave freely of advice and assistance. Especial thanks are due to Mr Brian Baker, also of the Department of Mines and Geology, who assisted the writer in the field and in other ways too numerous to mention.

I. INTRODUCTION

Searching through the somewhat scattered and certainly confused mass of writings which comprises the literature of structural petrology (and tectonics, of which it forms part), a reconnaissance geologist generally is at a loss to see how the apparently introspective principles and esoteric terminology so encountered can be of use to him in the routine mapping and interpretation of a large body of deformed rock such as any part of the Basement System of Kenya. It is true, indeed, that many of the techniques nowadays employed in structural analysis, especially on a microscopic scale, are so time-consuming as to be useless in a reconnaissance survey which must be completed in a limited period of time. But there are several fundamental principles of structural analysis a grasp of which makes easier and more accurate the interpretation of structures in deformed rocks, even in an investigation which must be conducted rapidly over a wide area. For this reason, in the regional study which forms the subject of this paper, some space is devoted to discussing some of the principles of structural analysis which are of use in a reconnaissance survey and help to generate in a geologist a "feeling" for structural geometry. There is available in the English language today /

today no general account of the principles and techniques of structural analysis that is of practical value to a reconnaissance geologist. The account which follows is not intended even partially to fill the need for a general text: rather is it intended to introduce, especially to the geologists of the Colonial Geological Surveys, the scope of statistical analysis of rock structures, and to outline some of the simpler principles and techniques of which a reconnaissance geologist can profitably make use.

It remains in this introduction to outline the significance which is attached by the writer to the term structural analysis. Structural analysis of a given body of rock is best considered to comprise three phases of investigation, as follows:

1. Geometrical analysis: that is, the study of structural geometry. The special feature of this phase of analysis is that it is concerned with direct observation of visible structures and it is descriptive. But a certain amount of inference and deduction generally has to be made in geometrical analysis, an amount which varies with the scale of the investigation.

2. Kinematic analysis; that is, the inference from phase 1 of the movements which, acting upon an earlier fabric, have produced the observed structural geometry.

3. /

3. Dynamic analysis: that is, the inference from phases 1 and 2 of the nature of the stresses responsible for deformation.

A reconnaissance geologist generally is concerned only with the first of the three phases of structural analysis: but, even in preliminary surveys, sometimes it is possible and desirable to draw kinematic and dynamic conclusions from studies of structural geometry. Particular attention in such instances should be paid to scale and homogeneity, because a movement picture or system of stresses deduced for one scale (for instance a single quarter-degree quadrangle) may have to be modified greatly when applied to a larger scale.

This paper is primarily intended for the field geologist and for this reason references to specialized literature are kept to a minimum. The principles which the writer thinks are useful in reconnaissance surveying are discussed and some of them are applied to the Turoka area. It must be stressed that the views expressed in this summary are those of the writer unless otherwise stated. But some attempt is made to tie those views into a philosophical framework similar to that of Sander and the great Swiss mega-tectonicians, Lugeon, Argand and Wegmann. A great debt also is owed to D.B. McIntyre through /

through whose efforts the study of structural geometry, now becoming an orthodox procedure, was initiated in Scotland.

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II. GENERAL FEATURES OF THE BASEMENT SYSTEM AT TUROKA

1. Preliminary Statement

The area to be described in detail is shown as a black rectangle on map 1. It is situated in Masai country about 50 miles south of Nairobi and is administered from Kajiado. The total area is about 40 square miles. The railway line from Kajiado to Magadi just enters the northern part of the area at Turoka station: the only access tracks are shown in maps 2 and 3.

Apart from a small outlier of Kapiti phonolite, the area contains only rocks of the Basement System. The nearest quarter-degree sheets which have been mapped by the Geological Survey of Kenya are shown in map 1, as follows:

1. Degree sheet 52, south-west quadrant: the Southern Machakos District, mapped by B.H. Baker (Report Number 27).
2. Degree sheet 59, north-west quadrant: the Sultan Hamud area, mapped by D.L. Searle (Report Number 29).
3. Degree sheet 58, north-east quadrant: the Namanga-Bissel area, mapped by P. Joubert (Report Number 39).

The Turoka area and the Namanga-Bissel area overlap for an area of 15 square miles.

The particular interest of the Turoka area which led to /

to the detailed investigation now is briefly outlined. The Basement System of the area is part of the Turoka Series named and briefly described by Parkinson (1913). It probably is the metamorphosed equivalent of a system of sedimentary rocks (including limestone and quartzite) together with associated igneous, volcanic and plutonic members. Similar rocks occur in the Basement System as mapped in the neighbouring quadrangles, and it seems likely that much of the Basement System in the southern part of Kenya resembles the Turoka Series both mineralogically and structurally. The problem encountered by the Survey was a structural one which came to light during the mapping by Joubert of what is the southern part of the Turoka area. Over most of the Namanga-Bissel area, of which this small problematical area also forms part, the strike of foliation in the Basement System is regularly north-north-west and the dip is regularly 20° to 30° to the east-north-east. On stratigraphical grounds, that is, on the resemblance in different localities between sequences of layered marbles, quartzites and gneisses, Joubert has postulated the existence of a number of large isoclinal recumbent folds about axes which are horizontal and parallel to the north-north-west strike of the foliation. Joubert also has recorded in the Namanga-Bissel area a regular trend (north 60° east) and plunge (20°) of pronounced linear /

linear structures lying in the foliation-surfaces. Because this lineation plunges down the dip of the foliation, and because the recumbent folds postulated by Joubert require a shortening or "transport" along a line trending east-north-east, this lineation has been interpreted by him as an "a-lineation" marking a direction and perhaps a sense of penetrative slip on the foliation (Joubert, 1956, MS in press). This general picture, however, is complicated in some places by sudden swings in strike and variations in dip of foliation. One such place is in the small expanse of bush common to both the Namanga-Bissel and Turoka areas. There, a low crescent-shaped ridge is formed by the outcrop of a thick layer of marble; the strike of the foliation on the ridge swings from the regional north-north-west orientation through a right-angle to east-north-east and the dips range from 20° to 90° . Such variations cannot be attributed to the effects of folding about horizontal axes trending north-north-west, to which can be attributed the regional phenomena. There appear to be three possible solutions to the problem posed by this and other similar structures found by Joubert in the Namanga-Bissel area, as follows:

1. /

1. The anomalous structures have been superposed in response to late movements upon the simple large-scale structures envisaged by Joubert.

2. The anomalous structures are earlier than the large-scale recumbent folds and represent a tectonic survival only partly overprinted by later movements.

3. The anomalous structures are not in fact anomalous but are homologous with all the important penetrative structures on all scales. If this is true, then the large-scale structures may be otherwise than as envisaged by Joubert.

In order to decide between these three possibilities, or to decide if there were yet another explanation, a detailed structural survey was made of the area surrounding Turoka, including the crescentic ridge of marble, followed by a structural analysis of orientation data.

2. General Account of the Turoka Area.

The average altitude of the area is about 5,600 feet and the greatest difference in altitude is about 2,000 feet. The area is bordered on the east by the high land of the Lemilebbu Hills, composed of quartzite and marble, and on the west by part of the Kapiti Plateau which owes its altitude to the protection /

protection from erosion of the underlying gneisses by a thin capping of resistant Kspiti phonolite. In the tract between these ridges are numerous low undulating hills and valleys which sometimes reflect the composition of the underlying rocks. In general, the marbles form the highest ground and the gneisses the lowest. Exposure is very variable, ranging from locally good on some of the ridges and in the river courses to non-existent in the wide alluvium-filled expanses between (see maps 2 and 3).

To serve as a base for the structural survey, a map showing the principle rivers and tracks and the railway was prepared on the scale of 1:28,800 from eight aerial photographs. This map has no ground control and no great accuracy. The spot-heights shown on map 3 were determined by means of a surveying aneroid and must be considered as only approximate. Mapping was done on the aerial photographs by means of "Kodatracer" overlays, and the results were transferred to the larger scale base map.

For reasons which are stated below, it was found unnecessary to differentiate between the different kinds of gneiss. The only exception is the gneiss in the core of the Turoka fold (see /

(see below) which is a lithologically uniform granulitic gneiss distinct from the generally non-granulitic gneisses enveloping the fold. Granulitic gneisses occur also in the south of the area but poor exposure makes their disposition uncertain.

The rock types in the Basement System which were differentiated and mapped are as follows (map 2):

1. Undifferentiated gneiss: this is the matrix in which are embedded the bodies of other composition. The gneisses range from uniform granitoid gneisses through biotite gneisses to hornblende gneisses and amphibolites. Many of the gneisses are garnetiferous.

2. Granulitic gneiss: this occurs in the core of the large and apparently rootless fold of marble described below. Quartz occurs in this rock in granulitic form as long flattened lenticles or ribbons.

3. Marble: generally a white or blue coarsely crystalline marble, in places very impure and with a marked foliation paralleled by thick layers of snow white diopside and other calcium silicates, and in other places very pure with no visible foliation. There are three main masses of marble:

- (a) the crescent-shaped outcrop in the southern part of the area;

- (b) /

(b) the ring-shaped outcrop at Turoka - the Turoka fold;

(c) the irregular outcrop of the Lemilebbu Hills.

Other small masses occur as shown in map 2.

4. Quartzite: there are many small layers and lenses of quartzite associated with the marbles: only the largest are shown on map 2. The greater part of the northern spur of the Lemilebbu Hills is composed of quartzite enveloping marble. The other important masses are to be found at the margins of the bodies of marble.

5. Pegmatites: these occur as bodies of various size both concordant and discordant with the foliation. None is shown on map 2.

It is beyond the scope of this paper to describe the petrography of these rocks; but reference is made to some of their microscopic features in the discussion of structures on a microscopic scale.

The lithological mapping yielded the information (neglecting the lineation symbols) shown on map 2. If topography is for the moment ignored, then this map can be considered to represent a plane horizontal surface cut through a three dimensional body of rock showing the intersection on this surface of the boundaries between important lithologically distinct /

distinct units within the body. The purpose of structural analysis, is primarily, as far as possible, to add a third dimension to this geometrical picture: and secondarily, to attempt a kinematic and dynamic interpretation of the body thus exposed.

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III. SOME PRINCIPLES OF STRUCTURAL ANALYSIS

1. Preliminary statement

This section outlines some of the principles and concepts of structural analysis an understanding of which the writer has found useful in field investigation of rocks deformed by flow. The discussion is intended to serve as an introduction to the field of structural analysis for field geologists who have had no previous contact with methods of statistical analysis. It begins with an account of homogeneity and scale in an effort to show how a view of the structure of a body of deformed rock, and of the movements and stresses which have operated in it, depends to a large extent on the scale on which it is taken. Then follows an introduction to the idea of symmetry, to its use in interpreting statistical orientation data and to its limitations. The next part of the discussion is concerned, from the viewpoint of statistical analysis, with the more important geometrical aspects of structures commonly occurring in deformed rocks, especially with foliations, folds and lineations, and to some extent with the patterns of preferred orientation of the commoner rock forming minerals (mica and quartz). The last part of the discussion branches out into the field of kinematics. There is an increase in the difficulty /

difficulty of the material discussed in this section. The concepts discussed are not easily grasped and a capacity to envisage structures and movements in three dimensions is necessary in the reader. Also, in this last part the opportunity has been grasped to bring into the discussion references to some recent contributions to the geology of the Scottish Highlands which are relevant to the study of the structures at Turoka. Particularly important are the concepts of $\underline{B} \perp \underline{B}'$ and $\underline{B} \wedge \underline{B}'$ -tectonics.

Some of the material discussed in this last part is not of immediate interest to a reconnaissance geologist. But it may arouse in him a desire to read further into the literature of structural geology, and help him to gain what is necessary to all structural geologists, namely, a feeling for the geometry, symmetry and essential unity of penetrative structures produced by flow in rocks.

2. Scale and Homogeneity.

Before introducing the concept of symmetry it is necessary to mention two interrelated concepts also of prime importance in structural analysis, namely, the concepts of scale and homogeneity.

Three /

Three absolute scales conveniently may be distinguished in structural analysis but boundaries between these scales are not rigidly fixed and different structural geologists have different views upon where they should be placed. The writer favours the following definitions:

1. Microscopic: This covers any field which can be examined adequately by means of a universal microscope stage; that is, the field of a single thin section. X-ray analysis of very small specimens which cannot be examined optically is not covered by this scale.

2. Macroscopic: This covers fields ranging in size from a single hand specimen to a single continuous exposure (generally but not always of small size) in which data can be measured with sufficient accuracy and continuity to allow determination of its overall structural geometry.

3. Megascopic: This covers fields of any size containing discontinuously observable structures. It stands apart from the other scales in that structures within megascopic fields are determined indirectly.

Although these absolute scales may be distinguished for convenience, there is no fundamental geometrical distinction to be drawn between them with regard to possible degrees of structural homogeneity. A strongly deformed mineral grain with /

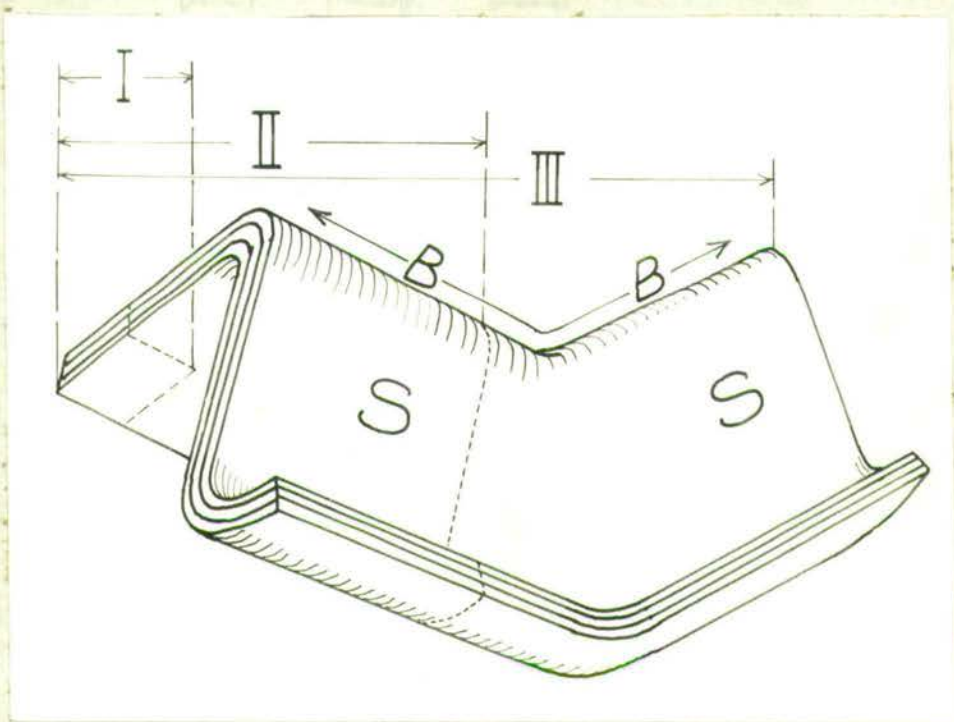


Figure 1. Fields of homogeneity with respect to S and B.

with twin and translation gliding can be as inhomogeneous on its own scale with respect to its own structural elements as can a mountain. There is, however, a general rule regarding the relation between homogeneity of fabric and scale in a given body of deformed rock, as follows:- for a given field, with respect to a given structural element, homogeneity of fabric increases inversely with scale. Therefore, to obtain a greater degree of structural homogeneity within a given field, the field must be examined on a smaller scale. This is one of the most important rules in structural analysis.

When discussing homogeneity in structural analysis it is necessary first, to distinguish between homogeneity of fabric and homogeneity of deformation, and second, to determine relative homogeneity on different scales with respect to specific structural elements. As an example of the use in structural analysis of homogeneity of fabric, the body shown in figure 1 is considered. The absolute scale is immaterial. A set of parallel surfaces (S) is cylindroidally folded (see below) about an axis (E) and the elongate structure so formed is bent. For this example it is assumed that the penetrative structures produced by the bending are confined to the immediate vicinity of the bend. Fields on various scales (I, II and III in /

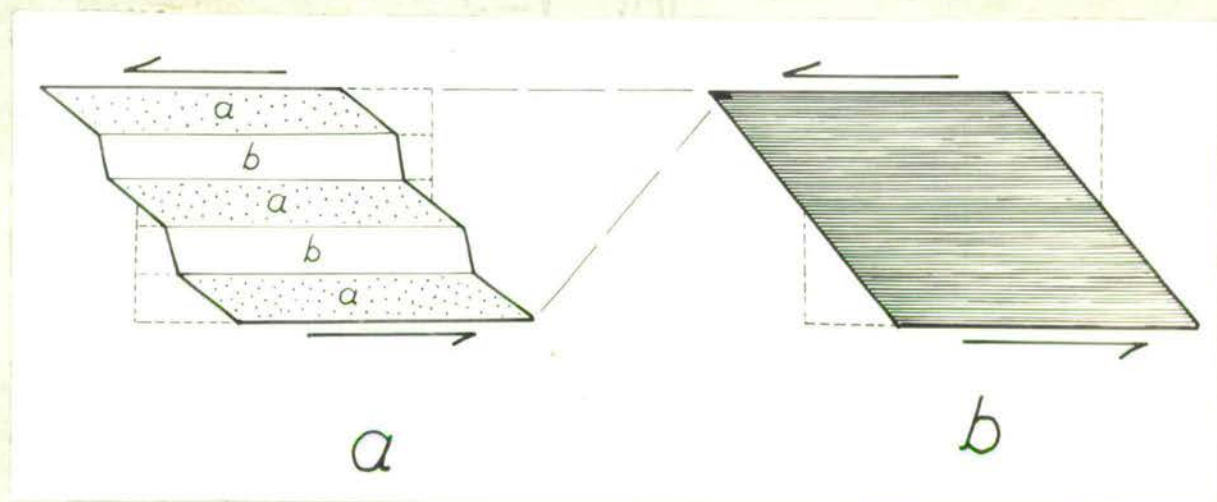


Figure 2. Change of statistical homogeneity of deformation with change of scale.

in figure 1) have the following degrees of homogeneity with respect to the orientation of S and E:

Field I is homogeneous with respect to both S and E;

Field II is inhomogeneous with respect to S but homogeneous with respect to E;

Field III is inhomogeneous with respect to both S and E.

If the cylindroidal folding of S is by flexural slip (S is the surface of slip), then degree of deformation in individual layers parallel to S of finite thickness can vary. Such a variation means that, although it is homogeneous with respect to the orientation of S, field I is not necessarily homogeneous with respect to those elements of the fabric which reflect the amount of penetrative movement distributed through any one layer of finite thickness. For instance, if slip on S is concentrated in certain layers (a in figure 2a) which separate layers in which deformation is less pronounced (b in figure 2a), then the fabrics in the layers a and b must be correspondingly inhomogeneous in certain respects. Plainly they are homogeneous with respect to the orientation of S; but if layers a are, say, pure quartz and layers b are, say, quartz plus feldspar, then it is probable that the degree of preferred orientation of quartz in layers a and b is different: that is, the field is inhomogeneous with respect to the degree of /

of preferred orientation of quartz. But because movements in layers a and b differ in amount only and not in kind the symmetry (see below) of the preferred orientation of quartz probably is homogeneous throughout. Alternatively, field I can be structurally homogeneous in all respects down to the granular scale. Many marbles and other monomineralic or mineralogically uniform rocks have such homogeneity.

Whether or not inhomogeneities of the kind just described are significant in structural analysis depends largely upon the size of the field considered relative to the scale of the inhomogeneities. On the scale pictured diagrammatically in figure 2a, slip on S is non-affine (see Knopf & Ingerson, 1938, pp. 75-76) and the field is inhomogeneous; but if this field is part of a very much larger field with the same kind of small scale inhomogeneity, then the fabric can be statistically homogeneous on the larger scale (figure 2b). This example is analogous to the affine deformation by slip of a thick pack of very thin cards. There is no slip in the cards themselves so that a straight line inscribed upon the side of the card pack before deformation becomes, after deformation, "stepped" on the scale of a few cards. On this scale the fabric and movement are inhomogeneous, whereas on the scale of the /

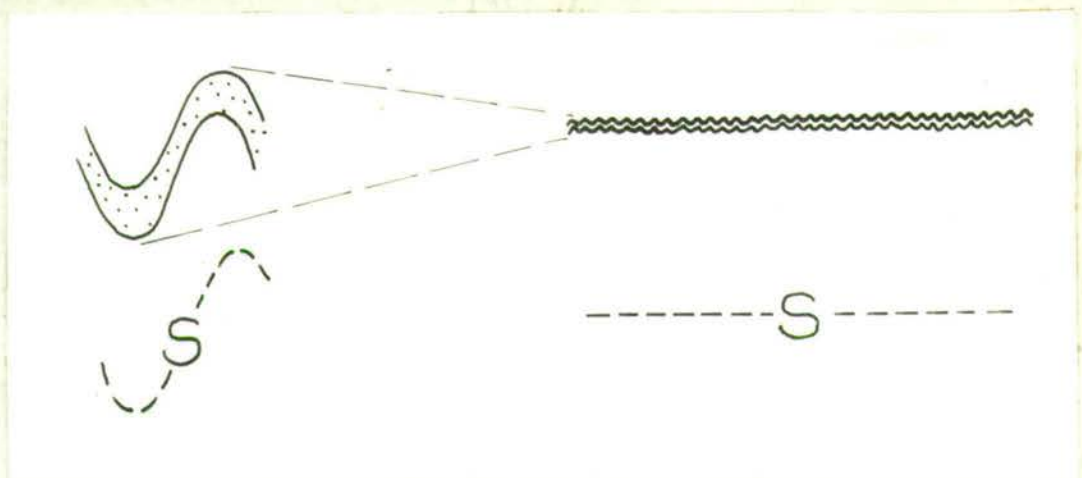


Figure 3. Flexural slip folding as a statistically homogeneous deformation on a large scale.

the whole pack fabrics and movement are statistically homogeneous. A similar state of affairs exists in some deformed rocks such as the Yule marble deformed "homogeneously" by experiment (Griggs and Miller, 1951, pp. 857-862), although in this instance deformation is not by slip on a single set of planar surfaces. In Yule marble each grain behaves in a manner decided by its own crystallographic orientation and the external stresses; but, because the grains are small relative to the whole specimen, the change in shape of the specimen is similar to what it would be for a homogeneous deformation.

There is thus no hard and fast correlation between scale and homogeneity unless the degree of homogeneity is established with respect to definite structural elements: and, even so, statistical homogeneity on a large scale with respect to a particular structural element sometimes can be established in rocks in which on a small scale the fabric is inhomogeneous with respect to the same structural element. This is not true only on scales involving study of grain orientation such as the example just cited. Differential behaviour of layers and bodies on any scale can give rise to the same kind of statistical homogeneity. For instance, if field II in figure 1 is part of a much larger field folded in the same manner (figure 3), then this large field may be considered to be statistically homogeneous /

homogeneous with respect to the orientation of S, which is statistically planar.

Because of the infinite variety of possible interrelations of scale and degrees of homogeneity, no absolute scale has a corresponding absolute homogeneity. For this reason there is no fundamental difference between structural analysis on the three absolute scales. A diagram showing preferred orientation of grains prepared from a single thin section can show a degree of structural homogeneity analogous to that of a diagram showing preferred orientation of macroscopic structural elements prepared from a large body of rock. This fact is important because there is a tendency, especially among British geologists, to look upon structural analysis on the microscopic scale as something fundamentally different from structural analysis on other scales. For this reason, microscopic structural analysis is rarely used in Britain, and, mostly improperly when it is.

3. The Concept of Symmetry in Structural Analysis.

One of the most important concepts in structural analysis is the concept of symmetry. The best account of the use and significance of symmetry in the study of rocks deformed by /

by flow is to be found in Knopf and Ingerson (1938, pp. 42-62). The use of symmetry in studies of the nature and effects of deformation is probably peculiar to geologists. Other workers dealing with deformation tend to use more precise methods of analysis of fields of stress and strain. But the concept of symmetry is invaluable in practical evaluation of the significance of orientation diagrams produced by the graphical methods of statistical analysis used in tectonics. With reference to the use of symmetry in structural analysis, the following facts are important:

1. Symmetry is defined statistically in the same fashion as homogeneity. Although the systems used to define symmetry in structural analysis are the same as some of those used to define the symmetry of crystal lattices, they possess none of the precision of the crystallographic systems.

2. In structural analysis, symmetry is used in three ways corresponding to the three phases of analysis. It may be used to describe fabric, movement (strain or distortion) and stress. Generally, only for an ideally homogeneous body deformed homogeneously do these three have always the same symmetry on all scales.

3. Symmetry must be considered together with scale. Since like /

like homogeneity, symmetry is defined statistically, it can vary with scale in a single field of deformation.

Symmetry of fabric and movement are of much more concern to a field geologist than is symmetry of stress. They are defined in terms of planes of mirror symmetry. In naturally deformed rocks only three systems need be considered: a fourth kind, axial symmetry (the symmetry of a cylinder), probably occurs rarely or not at all in nature. The three kinds of symmetry are, in decreasing order, as follows:

1. Orthorhombic symmetry - three mutually perpendicular planes of symmetry.
2. Monoclinic symmetry - one plane of symmetry.
3. Triclinic symmetry - no planes of symmetry.

In figure 4 are reproduced three actual examples of statistical orientation diagrams ($[0001]$ -axes of quartz grains) demonstrating the three kinds of symmetry. Figure 4a has orthorhombic symmetry (planes of symmetry AB, BC and AC), figure 4b has monoclinic symmetry (plane of symmetry AC) and figure 4c has triclinic symmetry (no plane of symmetry).

The foregoing remarks are introductory to the principle upon which the edifice of structural analysis can be said most heavily to rest. This principle may be called the principle of symmetry, or, as E.M. Anderson (1948, p. 122) has called it, "the /

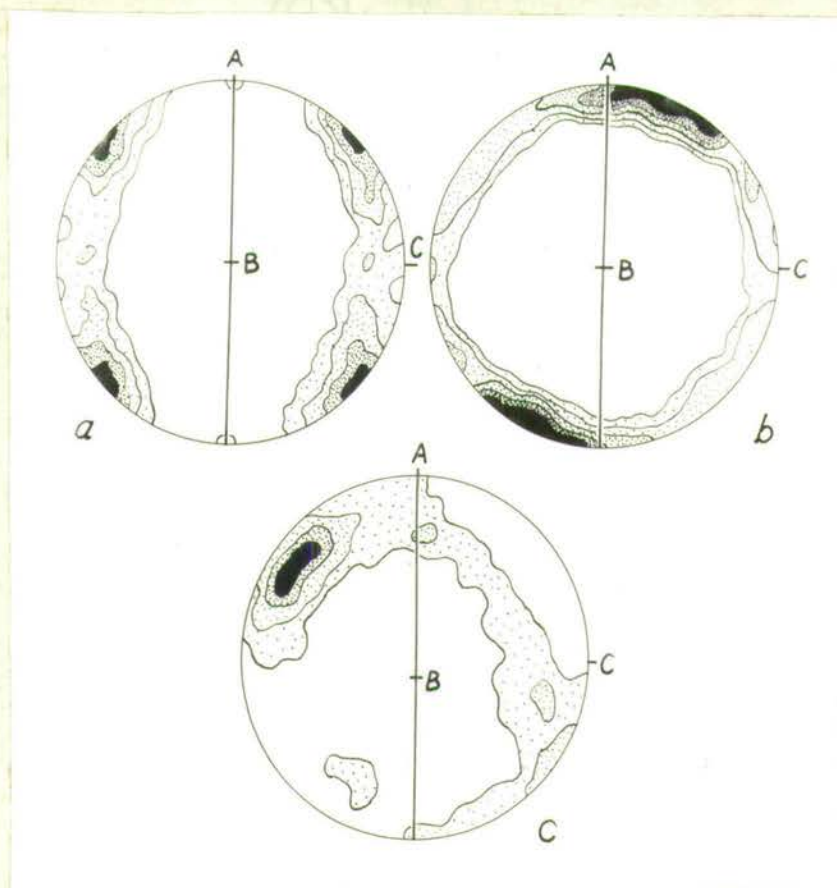


Figure 4. The three kinds of fabric symmetry.

- a. Orthorhombic symmetry; quartz, 300 [0001]
-axes from mylonized quartzite in the Moine thrust-zone, Stack of Glencoul, Sutherland, Scotland (by permission of J.M.Christie); contours, 1-3-5-8% per 1% area.
- b. Monoclinic symmetry; quartz, 361 [0001]
-axes from mylonized quartzite near Barstow, California, U.S.A; contours, 1-2-4-6-8%.
- c. Triclinic symmetry; quartz, 309 [0001]
-axes from quartz-rod on Ben Hutig, Sutherland, Scotland; contours, 1-4-7-10% per 1% area.

"the argument from symmetry". It is simply this: that the symmetry (the internal statistical symmetry) of the fabric of a tectonite expresses the symmetry of the movements which have affected it. In its simplest forms, unapplied to the deformation of rocks, the principle is taken for granted. The bending of grasses and the rippling of the surface of a sheet of water by wind are examples of the principle. Deposition of sediments in a flowing medium (current bedding) is a commonly observed and applied geological example outside the field of rock deformation. But apart from the irrefutable logic of the principle in all its applications there is, for the still sceptical geologists, support for the validity of the principle, with regard to rocks deformed by flow, given by the experiments of Griggs, Turner et al on Yule marble (see, for instance, Turner and Ch'ih, 1951, p. 905).

The principle of symmetry, as outlined, covers only the relation between symmetry of movement and symmetry of fabric. A system of external stresses also can be expressed in terms of symmetry: but only for an ideally homogeneous deformation of a homogeneous body can an analagous principle of symmetry be outlined to cover the relation between symmetry of stress and symmetry of movement. In practice, the principle governing the relation /

relation between symmetry of movement and symmetry of fabric also has to be modified to explain certain fabrics which apparently are exceptions to the principle (Weiss, 1955). It was intended to outline the reasons for these exceptions in this work but lack of space has made it necessary to transfer the material to a later paper. For the purposes of a reconnaissance survey mostly concerned with structures on a large scale, the principle of symmetry can be accepted.

Finally, it must be stressed that the symmetry of a fabric can be determined only after considering the symmetry of all its penetrative structural elements (foliation and other g-surfaces, folds, lineations, patterns of preferred orientation of mineral grains and so on). Joints and other impenetrative structures are not considered here. Commonly, the symmetry defined by one structural element does not agree with that defined by another: or two elements each with high symmetry may combine to define a lower symmetry for the fabric as a whole.

4. Structural Geometry.

General statement: The problem involved in the first phase of structural analysis is basically a philosophical one. A certain way of looking at deformed rocks is required in a geologist to make possible the accurate visualization in three dimensions of the body of rock of which he sees only two dimensions incompletely in the form of a geological map. This philosophy is best described broadly as the geometrical approach to structural geology. A body of rock deformed by flow has an internal geometry, and it is the main function of the structural geologist as far as possible to determine this geometry and represent it in some fashion which can readily be understood and assimilated by another observer. This is the descriptive phase of structural analysis to be followed later by the interpretive phases of kinematic and possibly dynamic analysis.

If the effects of topography are ignored, then a geological map showing only boundaries between formations or lithologically distinct units is a two dimensional representation of a solid body. The third dimension can be represented in several ways:

1. The most commonly employed method is the structural map. This is a map which shows, ideally in addition to boundaries between /

between formations, symbols which define the orientation and distribution of structural surfaces, such as foliation and bedding, and of structural axes, such as fold axes and lineation. For such a map to succeed in its purpose of conveying a feeling of "depth" to an observer a great many measurements must be recorded and the symbols used on the map must be chosen with care. For instance, in representing the attitude of a structural surface, the symbol which shows a strike-line and a dip-mark is a far more satisfactory means of conveying an impression of a dipping surface than is the dip-arrow used by the British and Colonial Surveys which gives no such impression and should be abandoned. On the other hand, a single arrow should be used to denote the trend and plunge of linear structures since the "grain" thereby imparted to the map agrees with the projection trace of the linear element. Examples of this kind of representation are given by maps 2 and 3. The "grain" of the two maps is quite different, as it should be. If dip arrows had been used for the foliation the two maps would give a very similar visual impression.

2. Another means of locally representing the third dimension is by means of cross sections or profiles drawn generally normal to the plane of the map. This method is legitimate only in so far as it is a representation of facts. Too often
a /

a profile is a product of a fertile imagination rather than an accurate construction based upon observed data. For a profile to have validity and significance it must be constructed geometrically as a sequel to a statistical analysis (Wegmann, 1929; McIntyre, 1951). One important feature of a profile is that it has full significance only when drawn through a body which has monoclinic or orthorhombic symmetry, that is, a body which has one or more directions within it along which the geometry is statistically unchanged. To have full significance, a profile must be drawn normal to such a direction: it then becomes a transverse profile. For a body with a slight degree of triclinic symmetry, a transverse profile can be sometimes constructed artificially by dividing the body into homogeneous subdivisions with monoclinic symmetry, and by producing a composite profile from the partial profiles so obtained (Lugeon, 1930). But, although such a profile may be represented upon a plane surface, it corresponds to no plane surface within the actual body: it is merely a qualitative representation of structural geometry and as such has its place in structural analysis. Further details regarding the construction of profiles are given below.

3. The least used but most satisfactory means of representing structures in three dimensions is by plotting structural data /

data on the lower hemisphere of an equal-area projection. If the structures plotted have a uniform significance and orientation, then this mode of representation is probably the most forceful in conveying an impression of the geometry and symmetry of the body. A projection of this sort has the disadvantage of showing only orientation and not position of measured data and for this reason it is best used in conjunction with a geological map; but it has the great advantage of graphically representing statistical variation, allowing immediate recognition of degrees of structural homogeneity and symmetry and modes of variation in the orientation of structural elements throughout a given body.

Investigation of structural geometry is not confined to foliation, folds, lineations and other structures on the macroscopic and megascopic scales. The geometry of fabric elements on a microscopic scale can be just as important a facet of structural analysis, sometimes yielding information obtainable in no other way. In general, the method most commonly used to plot structural data measured by means of a universal stage is the equal area projection; but distribution of elements is sometimes shown by means of an A.V.A. map (Ram-sauer, 1941) which is analogous on the microscopic scale to a structural /

structural map on the megascopic scale.

Foliation as a form-surface: The geometrical approach in structural geology consists in the study of the internal geometry of a body of rock, that is, the shape or form of penetrative structures which can readily be observed and measured. On megascopic and macroscopic scales the penetrative structures with which a reconnaissance geologist largely is concerned are:

1. A visible set or sets of parallel surfaces of inhomogeneity defined either by lithological variation or preferred dimensional orientation of mineral grains or both. The descriptive term foliation is used to denote these surfaces in deformed rocks.

2. Folds in a set of such surfaces.

3. Lineations lying in the surfaces.

In this section foliation is discussed from a geometrical point of view, and it is impossible to do this without making reference to the folds which commonly occur in it. Geometrical aspects of folds and lineations are discussed in the following two sections.

Most deformed rocks show a single set of surfaces which qualify to be called a foliation. There are commonly paralleled /

paralleled by layers of different composition which have been derived either directly or indirectly from bedding (in rocks initially sedimentary), or which have been produced from an initially statistically isotropic or anisotropic fabric (in rocks initially other than sedimentary) by the effects of movement and metamorphic differentiation. Other sets of penetrative surfaces or planes are commonly present in foliated deformed rocks; in some fabrics they are defined visibly by preferred dimensional orientation of mineral grains or a subsidiary layering; in others they are detectable only by statistical analysis. But usually one set of surfaces is much more prominent than any other and is selected as the foliation. On the other hand, if one set of surfaces is in process of forming out of another by transposition (Knopf and Ingerson, 1938, pp. 189-190) and both sets are more or less equally developed, then attention must be paid equally to the geometry of both.

In foliated rocks it is with the geometry of the foliation - with its attitude, if planar, and with the style and orientation of all folds which occur in it, if it is folded - that the structural geologist is primarily concerned. The resemblance between foliation in many deformed rocks and sedimentary bedding sometimes stimulates geologists to attempt stratigraphical /

stratigraphical study of the rocks in the same fashion as they would study sedimentary rocks. Occasionally, stratigraphical columns are erected and argued about; and then follows a further, often disastrous step (logical and correct in sedimentary rocks, but hardly, if ever, correct in rocks deformed by flow) of correlating one column with another and so deducing major structures. Such an approach to the structural study of rocks deformed by flow is unsound for two main reasons:

1. It omits entirely a geometrical study of foliation, substituting for an actual determination of structures in three dimensions a preconceived view of geometry based upon the simple structures commonly observed in sedimentary rocks. The commonest error made is the assumption of a fold axis parallel to the strike of dipping foliation (for a criticism of this basic assumption, see McIntyre, 1952, p 263). The reason for this error lies in the strong control which the initial planar-horizontal fabric of sedimentary rocks exerts upon the structures (generally folds in bedding) which are produced in response to a simple plane deformation such as a horizontal squeezing.*

Flow /

*"Squeezing" is translated from the German term Einingung (Sander, 1948, p. 48). It is used in this paper to denote an external non-rotational strain that can be described in terms of one or two mutually perpendicular directions of shortening or compression either tangential or normal to the surface of the earth.

Flow in such a primary deformation is almost invariably by slip on the bedding, and the axes of the flexural slip folds so formed develop only with an orientation which is, like that of the bedding, statistically horizontal. For this reason, the fold axes in most weakly deformed sedimentary rocks are either horizontal or very gently plunging. But strongly deformed rocks, which may have suffered one prolonged deformation or superposed phases of deformation, do not have, as a general rule, such a simple structure. Fold axes in these rocks plunge regularly or irregularly at any angle; axial surfaces of folds are planar and lie at any angle to the horizontal, or they are curved and irregular. In addition, phenomena of solid flow involving slip on flow surfaces other than the foliation commonly operate in such rocks giving rise to slip folds, lineations and other structures with complex geometry.

2. The "stratigraphical approach" presupposes that the differential compositional layering parallel to the foliation is a true sedimentary bedding of very great extent parallel to the layers. In some metamorphic rocks foliation is undoubtedly mimetic after bedding and a study of the stratigraphy and of preserved sedimentary structures, such as current bedding, may give a key to the geometry of the foliation on a large scale. But such studies should be made as a corollary to and not as a substitute /

substitute for a geometrical study. However, rocks which have suffered strong deformation involving penetrative movement, as well as metamorphic effects deriving from other causes, commonly possess a compositional layering which superficially resembles bedding. Such layers are generally of great areal extent relative to their thickness and are like flattened lenses in shape (Knopf and Ingerson, 1938, pp. 189-190). A foliation made up of such discontinuous overlapping layers is commonly to be observed in rocks formed from sedimentary or non-sedimentary rocks by one or more phases of deformation involving transposition of bedding and other surfaces of inhomogeneity by phases of folding and shearing. In such rocks, sedimentary structures may survive a certain degree of deformation in competent layers as a result of concentration of movement in incompetent layers (for instance, preservation of current bedding in a layer of quartzite enclosed in intensely deformed mica schist). The differential behaviour during deformation of rocks of different competence and the consequent effect upon stratigraphy cannot be emphasized too strongly.

Although foliation in a deformed rock does not have always the same genetic significance as bedding in a sediment, it is, nevertheless, with geometry of foliation that a structural geologist /

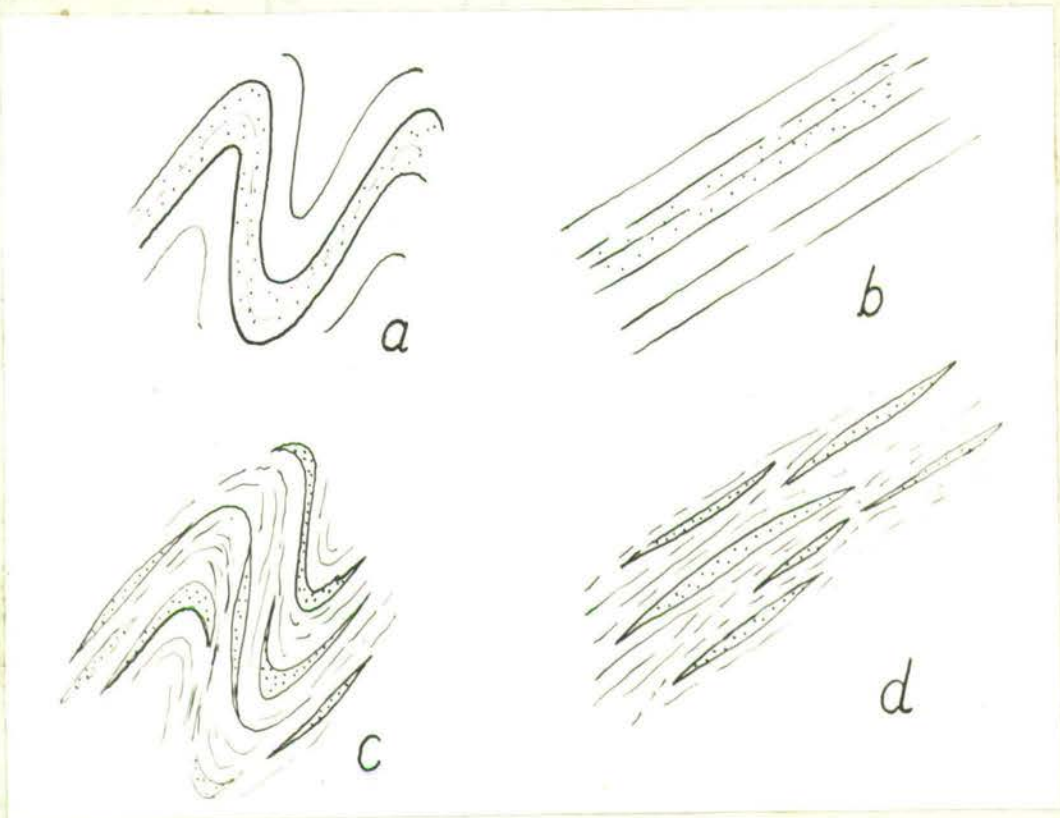


Figure 5. Folded form-surfaces.

geologist is primarily concerned. But he is much less concerned with the extent of individual layers than he would be were the rocks sedimentary and the layers bedding. The unlimited lateral extent allowed to sedimentary beds cannot necessarily be supposed to apply to discrete layers parallel to foliation. Rather, surfaces of foliation must be looked upon only as defining a structural form with a geometry determinable in three dimensions. The descriptive term form-surface has been used (McIntyre and Weiss, 1956) to describe this concept of foliation or bedding. Wegmann (1929, p. 108) has emphasized the fact that whether or not a given layer is attenuated in any direction by lensing is immaterial in the study of foliation as a form-surface. This fact is shown diagrammatically in figure 5. Figures 5a and 5b show subparallel sided layers folded cylindroidally (see below) and viewed respectively parallel and normal to the fold axis. Figures 5c and 5d show overlapping lenticles folded and viewed in the same fashion. The statistical geometry of the folded surfaces is the same in the two examples; the only difference between them is a lower degree of parallelism of the foliation with the fold axis in the example of the folded lenticles; but if the lenticles are thin relative to their lateral extent then this difference is inappreciable. The form-surface is the same in the two examples /

examples. This fact is important in the construction and interpretation of tectonic profiles by axial projection of cylindroidal structures.

Geometry of cylindroidal folds: Folds (especially flexural slip folds) can be looked upon in a broad fashion as the expression, by slip upon the folded surfaces, of a crustal shortening. In orogenic terms a crustal shortening acts in the first instance upon a statistically planar and horizontal set of surfaces of inhomogeneity (sedimentary bedding, sills of igneous rock, lava flows and so on) and, as already pointed out, the axes of flexural slip folds which form in response to a simple biaxial strain are horizontal. This ideal orientation is only statistically achieved. On a small scale, a fold axis of this kind is not exactly horizontal any more than it has everywhere the same trend; on a large scale also, culminations and depressions in the plunge of a fold axis commonly accompany variations in trend reflecting compositional heterogeneity in the deformed body or a degree of triaxial strain or both. Similarly, the ideal monoclinic symmetry of cylindroidal folds is generally realized only statistically; even on a small scale, triclinic symmetry is by no means uncommon.

However /

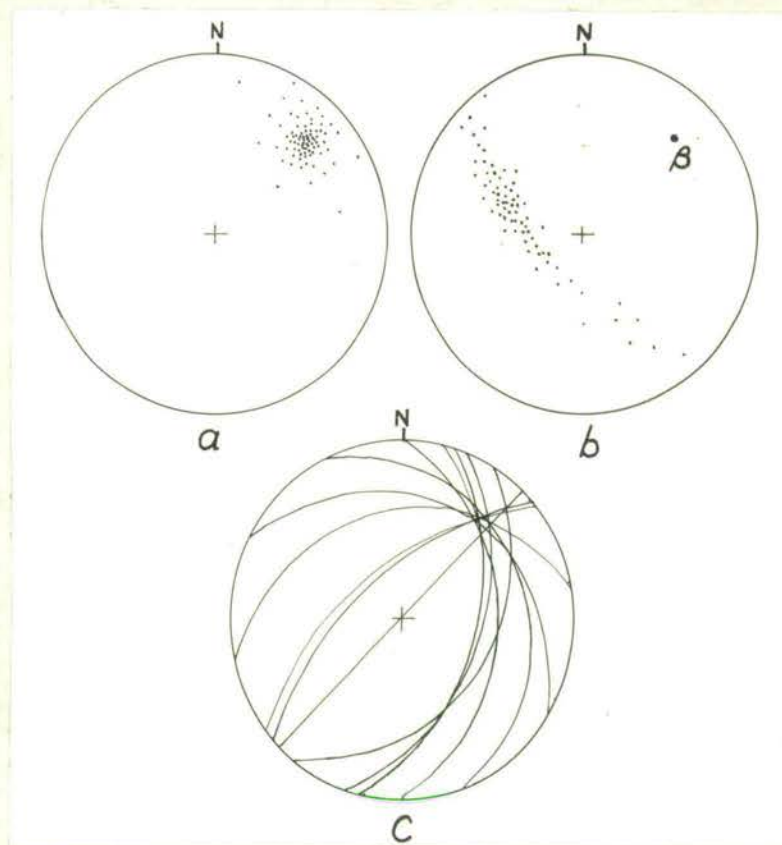


Figure 6. Graphical representation of orientation of penetrative structures on lower hemisphere of equal area projection (diagrammatical).

- a. Lineations.
- b. Π -poles (Π -diagram).
- c. Traces of \underline{S} ($\underline{\beta}$ -diagram).

However, the overall symmetry of a large body of deformed rocks can be triplanic, and yet can be easily divisible into smaller fields each of which is homogeneous with respect to the fold axis and has statistical monoclinic symmetry (for instance, the High Calcareous Alps of Switzerland). In each such homogeneous field the plotting on an equal area projection of measured fold axes shows them to lie in a pronounced maximum which corresponds in the field to a sheaf or bundle of axes the preferred orientation of which is the regional fold axis. The axis of intersection of syngenetic shear surfaces and the axes of syngenetic elongate bodies such as boudins, rods or mullions statistically define the same maximum (figure 6a).

Another graphical method of demonstrating the same geometrical relationship of the foliation or other syngenetic surfaces (\underline{S}) to the axis of folding or shearing (\underline{B}), useful where folds are too large or too poorly exposed for the orientation of fold axes to be directly measured, is by the plotting of measurements made macroscopically on planar positions of \underline{S} either as poles (normals to the planes) in the form of a $\underline{\Pi}$ -diagram (figure 6b) or as traces in the form of a $\underline{\beta}$ -diagram (figure 6c). In the $\underline{\Pi}$ -diagram, the axis of the great circle defined by the spread of the $\underline{\Pi}$ -poles corresponds, in the $\underline{\beta}$ -diagram /

β -diagram, to the statistical maximum of intersections of the great circles, which are the traces of S , and represents the statistically defined regional fold axis. This geometrical relationship holds true only for a body with monoclinic symmetry. Likewise, π - and β -diagrams have significance only for fields homogeneous with respect to a fold-axis. These methods of representing the geometry of axes and surfaces are the basis of all graphical methods of structural analysis.

So far in this discussion no explanation has been given of the term cylindroidal as applied to folds. The term fold, when applied to structures in deformed rocks, denotes a curved arrangement of a visible set of parallel surfaces, produced by flow in response to applied stress. Several mechanisms are involved in the formation of folds, flexure and slip being the most important; and great variation is possible in the geometrical form of folds, as seen in profile, and in the orientation of their structural elements (axes, axial surfaces and so on). But, irregardless of genesis or style, a fold can be described as cylindroidal if it has a fold axis as defined in the following way, " . . . the nearest approximation to the line, which, when moved parallel to itself in space, generates the fold. The utility of this definition lies in the fact that many complex folds maintain remarkably constant profiles /

profiles (sections at right angles to the axis) even when the sections are spaced at distances many times greater than the amplitude". (Clark and McIntyre, 1951a, p. 584). From this definition it follows that a π -diagram for an ideally cylindroidal fold shows all π -poles lying on a single great circle of the projection. But folds are rarely ideally cylindroidal, and the accuracy of determination of a β -axis depends to a large extent upon the location and number of the measurements made upon a statistically cylindroidal fold. If a fold is markedly cylindroidal, then a few measurements generally suffice to show this; on the other hand, if a fold is not markedly cylindroidal but still statistically cylindroidal on the scale considered, then a very large number of measurements may be necessary. For instance, a few measurements made on the structure shown in figure 7a may not show that it is statistically cylindroidal (figure 7b); whereas a large number of measurements from the same field may show this clearly (figure 7c). Whether or not a fold is to be considered cylindroidal will depend upon the nature of the structural problem and the scale of the investigation. Experience is an important factor in making a decision because all gradations between cylindroidal and non-cylindroidal structures exist.

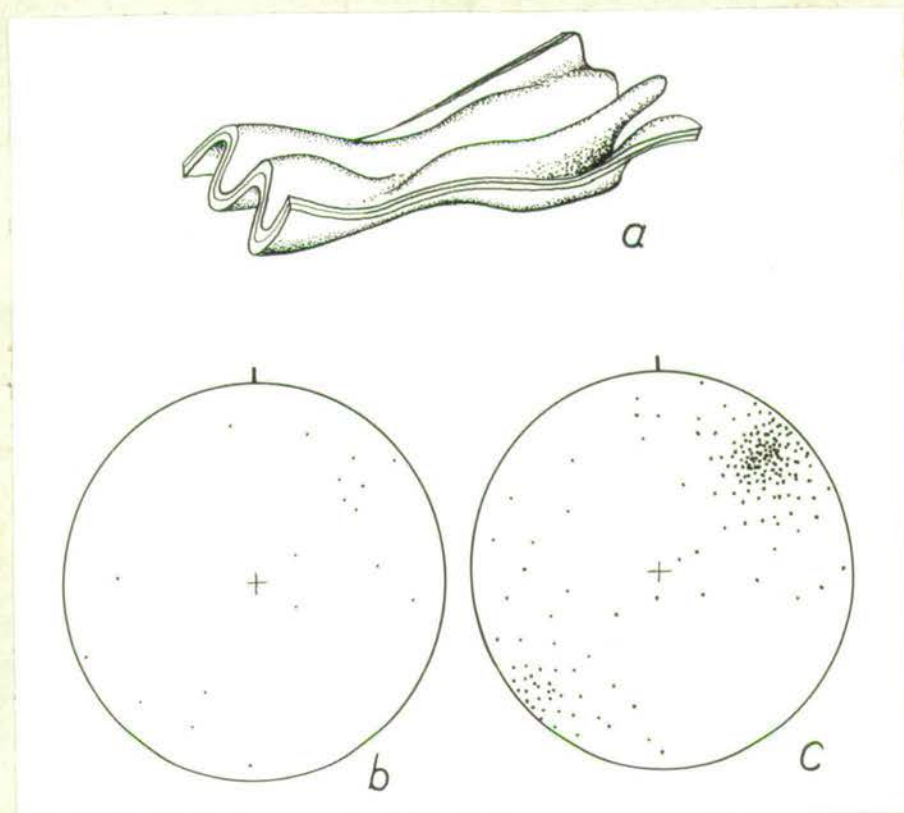


Figure 7. β -diagram from statistically cylindroidal fold.

A Π -diagram is most widely used to determine the axes of folds indirectly in the manner just outlined, but it has a subsidiary and less precise use in determining features of folds as seen in profile. As an example of this usage, in figure 8a are shown Π -poles measured in a field homogeneous with respect to a fold axis. The Π -poles lie in a girdle which defines the β -axis and they are arranged also in a strong maximum elongated slightly in the plane of the girdle. Outside this maximum the spread around the girdle is approximately uniform. The Π -poles represent measurements made with approximately uniform distribution throughout the field of investigation and the diagram is thus a measure of the frequency of occurrence of individual orientations of \underline{S} in this field. If folds exist, then they can have only a certain range of forms. Possible profiles for the folds are shown in figures 8b and 8c. They could be closely appressed folds symmetrical about a moderately dipping axial surface (figure 8b); or they could be more open but asymmetrical folds with an axial surface of greater inclination to the horizontal and one set of limbs longer than the other (figure 8c). Profiles like these would give the distribution of points on the Π -diagram. If small scale folds occur corresponding to either of the above /

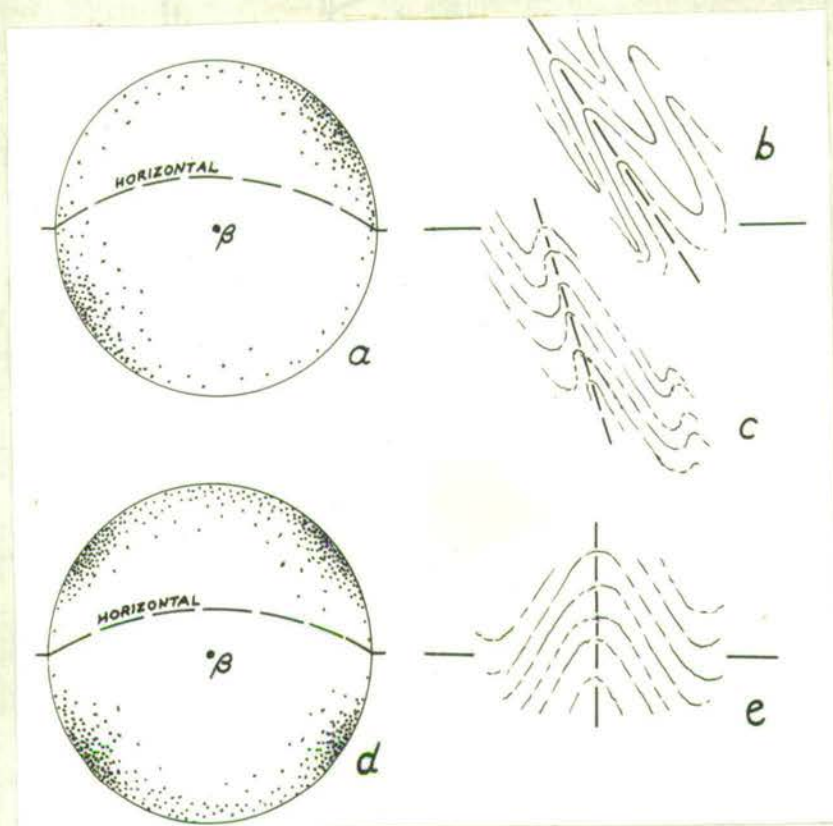


Figure 8. Determination of form of folds from Π -diagram (diagrammatical).

above profiles, then it is probable that the large scale folds too are of that kind. Structures produced by flow tend to be homologous on all scales.

A Π -diagram with two distinct similar maxima of the kind shown in figure 8d suggests symmetrical open folds with vertical axial surfaces (figure 8e).

Lineation: The term lineation has been defined by E. Cloos (1946, p. 1) as "a descriptive and non-genetic term for any kind of linear structure within a rock". For present purposes, this definition is best narrowed to include only penetrative linear structures lying in penetrative fabric surfaces. This restriction excludes linear structures such as impenetrative slickensides on foliation, joints and other surfaces, and linear structures on impenetrative surfaces (such as joints) parallel to the trace of another penetrative surface.

There are three main types of visible lineation:

1. Lineations caused by folding on a microscopic scale of a fabric surface. This structure is homologous with folding on a larger scale.

2. Lineations caused by elongation of fabric elements such as individual grains, groups of grains, small heterogeneous inclusions, and so on.

3. /

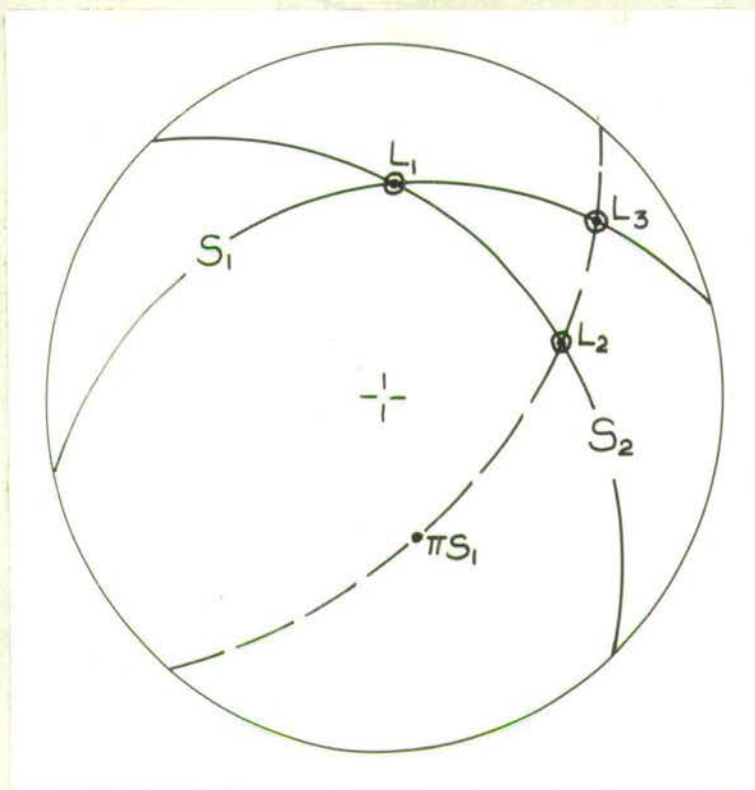


Figure 9. Geometry of projection-trace of lineation (type 4).

3. Lineations caused by intersections of mutually inclined sets of fabric surfaces. A parallel lineation appears in each set of surfaces.

All three types of lineation generally lie in a foliation, but fabrics occur in which lineations of type 2 apparently are unconnected with a fabric surface. A particular lineation can be a combination of any of these three types.

A fourth rather different type of lineation may conveniently be distinguished:

4. Lineations caused by the trace on one fabric surface of the projection of a lineation lying in another. In the same fashion as one surface intersects another to leave a linear trace (lineation of type 3), so a lineation lying in one surface can leave a linear trace on another inclined surface (Clark and McIntyre, 1951b, pp. 757-758). The geometry of this trace is shown in figure 9. S_1 and S_2 are two fabric surfaces intersecting in L_1 which is a lineation of type 3. But S_2 contains a second lineation of type 1 or 2 (L_2). This lineation leaves a trace on S_1 at L_3 parallel to its projection on S_1 . This trace (given by the intersection on S_1 of the plane normal to S_2 containing L_2) is a lineation of type 4.

Lineations are important kinematic indices, especially in /

in fabrics with monoclinic symmetry. In such fabrics, lineations of type 2 can be either parallel or normal to the plane of symmetry, but lineations of type 1 and 3 must always be normal to the plane of symmetry. Lineations of type 4 occur only in fabrics with triclinic symmetry.

The relation between lineation and movement has proved to be one of the most controversial problems of modern structural geology. Because the same problem has arisen in the Turoka area it is discussed at some length below in the section dealing with kinematics. To be emphasized here is the variety of lineations in deformed rocks and the necessity of studying all features of the geometry and symmetry of fabrics in which they occur. Only such studies enable a geologist to decide whether the measurement of lineation will be of assistance to him in interpreting the structure of a body of rock. To measure lineations the nature of which and the relation of which to other structural elements in a fabric are unknown is a waste of a geologist's time.

Grain orientation: Study of preferred orientation of grains of certain minerals sometimes yields information about the behaviour of a rock during deformation additional to that obtained from study of structures on macroscopic and megascopic scales.

Study /

Study of grains is essentially a study of components involved in componental movements and the information so obtained helps in the construction of a movement-picture for the small scale strain. It is particularly helpful in establishing which surfaces in a fabric have acted as surfaces of slip. Also, symmetry of movement is generally demonstrated clearly by the symmetry of orientation diagrams.

Because of the experimental work recorded by Griggs, Turner and others, the behaviour of calcite in deformed marble and dolomite in deformed dolomite rock is well understood. But marbles and dolomite rocks generally form only minor constituents of large bodies of deformed rock, and, on account of the high plasticity of dolomite and calcite, their behaviour during deformation may not typify the behaviour of the body as a whole. In addition, although interpretations (based upon experimentally obtained data) of the microfabric of marbles and dolomite rocks are more complete and accurate than interpretations of the microfabric of other rocks, the time-consuming nature of the techniques of measurement involved means that, as a general rule, such studies must lie outside the scope of a reconnaissance geologist. The same is true of other techniques of geometrical analysis on a microscopic scale, such as A.V.A.

But /

But in the view of the writer there are two common rock forming minerals, the preferred orientation of which can be established readily, that commonly repay in valuable kinematic information the extra time spent on their measurement. These minerals are quartz and mica.

Because of its almost ubiquitous presence in any large body of deformed rocks, quartz is the most frequently studied mineral in structural analysis on a microscopic scale. Preferred orientation of $[0001]$ -axes can be determined rapidly and accurately from a single thin section, whatever the degree of preferred orientation may be. If measurements are plotted on partial diagrams (diagrams showing orientation of $[0001]$ -axes in different parts of a single thin section), then some guide to homogeneity of preferred orientation on a microscopic scale also can be obtained from a single thin section (Weiss, 1954, figs. 59 and 60).

On the basis of symmetry, orientation diagrams for quartz fall into three groups; but there is great variety in the form and detail of the patterns. With respect to the Turoka area, the following commonly occurring types of pattern are important:

1. The first type of pattern has monoclinic symmetry and takes the form of a girdle with one or more peripheral maxima inclined /

inclined to foliation or other demonstrable surface of slip. All visible or statistically defined slip surfaces intersect in a common axis which is also the axis of the girdle of $[0001]$ -axes. Where megascopic lineations or flexural slip folds are associated with these girdles, they coincide with the axes of the girdles. There are many varieties of this fundamental type reflecting variations in intensity of deformation, composition, chronology of deformation and crystallization and number of intersecting slip surfaces. In some varieties the girdle is incomplete and a strong maximum is inclined at a low angle to foliation or other important slip surface. The most important feature of the type is its monoclinic symmetry and the demonstrable presence of a single set of slip surfaces or several sets of non-equivalent slip surfaces. An example is given in figure 4b.

2. The second group of diagrams is characterized by orthorhombic symmetry. The patterns range from a single strong maximum at or near the foliation through two such maxima situated symmetrically on either side of the foliation at various angles, to a type in which the maximum or maxima spread into two complete or incomplete girdles intersecting at or near the maxima and symmetrically inclined at less than 90° to the foliation. /

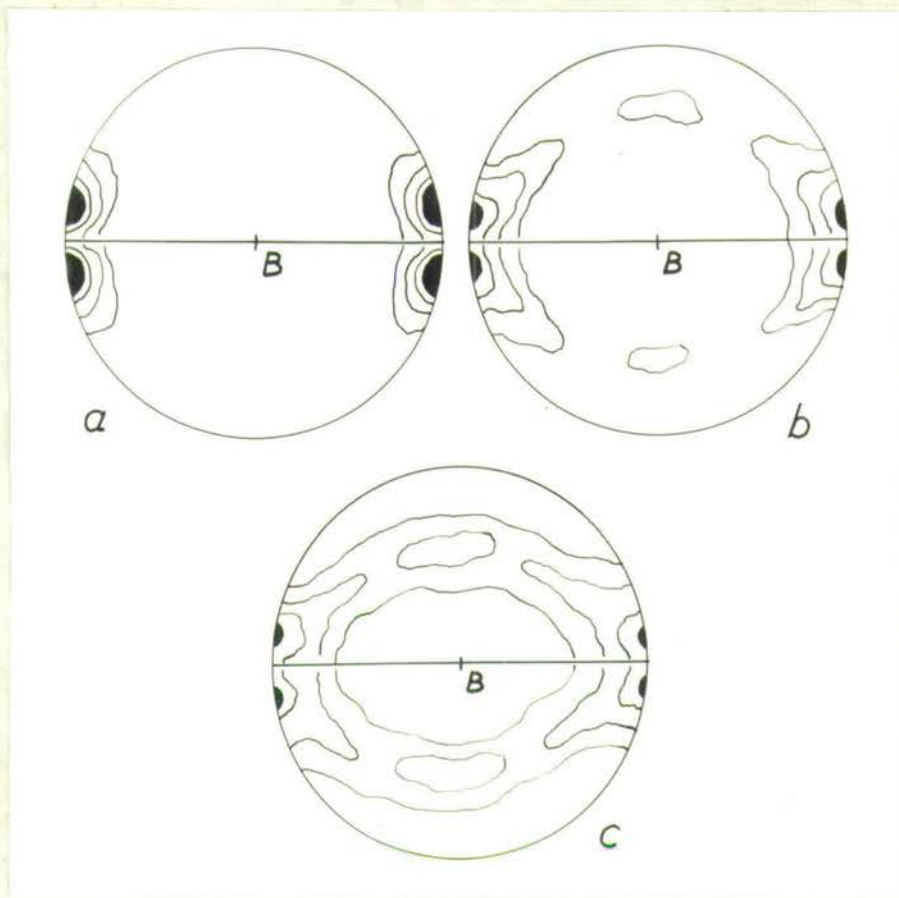


Figure 10. Variations in the (0kl)-girdle type of orthorhombic orientation pattern for $[0001]$ -axes of quartz (diagrammatical).

foliation. This sequence is shown in an idealized form in figure 10 a, b and c. There are infinite variations in detail on this general theme.

3. Any of the above types of pattern may show sufficient asymmetry of pattern for the symmetry to be considered triclinic. One of the two oblique girdles may be consistently more pronounced than the other, or the foliation or other fabric surface may be asymmetrically oriented (figure 4c). Such departures from monoclinic or orthorhombic symmetry may reflect local variations in the movement picture which are statistically insignificant on a larger scale; or triclinic symmetry may be observed consistently through a larger field reflecting non-plane deformation.

The use of the preferred orientation of quartz in kinematic interpretations is an empirical one. Even today, there is no general agreement on the mechanism by which quartz acquires a preferred orientation in deformed rocks, although it seems that cataclasis and recrystallization are far more important in this respect than intracrystalline plastic flow; but this fact does not invalidate the empirical use of patterns of preferred orientation in determining geometry and symmetry of flow. The most important information obtained from a study of /

of the preferred orientation of quartz is the symmetry of movement of which quartz, in some rocks, is a particularly sensitive indicator. This is true, of course, only in rocks in which quartz is sufficiently plentiful or in the correct mineralogical environment to participate actively in componental movement. The most suitable rocks in which to study preferred orientation of quartz are pure quartzites, in which quartz can show a very high degree of preferred orientation; but quartz is generally an active structural component in any fabric in which:

- (a) it is sufficiently plentiful to ensure that a majority of intergranular contacts in the rock are between quartz and quartz, whatever the accompanying minerals may be;
- (b) it is associated with minerals, such as feldspar, which deform less easily than quartz, even if most of the contacts in the rock are not between quartz and quartz.

In rocks in which quartz is subsidiary in amount to readily deformed minerals such as calcite, quartz grains can participate passively in deformation and acquire no preferred orientation (see, for instance, Weiss, 1954, pp. 51-58).

The importance of mica in fabric analysis lies in its tendency to become oriented with (001)-planes parallel or sub-parallel to fabric surfaces which may be expressed visibly in no other way. Determination of fabric symmetry based upon study /

study of macroscopic structures may have to be modified after study of preferred orientation of mica. In some fabrics, the preferred orientation of quartz and mica have different symmetry. This does not mean necessarily that the fabric has undergone more than one deformation, as is commonly supposed. Mica can participate passively in deformation in rocks of certain composition and yet, because of its inequidimensional habit, modify the symmetry of fabric. A fabric of this kind has been described by the writer (Weiss, 1955) from Anglesey off the coast of Wales, but the problem it raises is outside the scope of this discussion.

Any technique of structural analysis on a microscopic scale employed by a reconnaissance geologist must be rapid and must yield information additional to that obtained by analysis on larger scales for the analysis to be worthwhile. Commonly, the additional information obtained from microscopic structural analysis is of a kind that, although assisting greatly in the construction of a small scale movement picture, is of little assistance in making rapid large scale structural syntheses. But occasionally, as at Turoka, a small amount of statistical analysis with a universal stage extends an interpretation made on a larger scale to a microscopic scale and thus is worthwhile.

5. Kinematic Interpretation of Fabrics.

General observations: Detailed kinematic and dynamic interpretations of structural geometry must be preceded by very complete study of a deformed body on all scales. For this reason, such interpretations must lie outside the scope of a reconnaissance survey. The following general observations may help to outline some of the difficulties involved.

Kinematic analysis can be made in two ways (Sander, 1948, p. 171):

1. It can be made by constructing a movement picture.

On a microscopic scale this is done by considering the nature of componental movements which have occurred in a fabric during deformation. Movement pictures can also be constructed for scales other than microscopic by studying macroscopic and megascopic structures. For instance, a flexural slip fold denotes a shortening of the deformed body in which it occurs in a direction normal to the fold axis. It may be impossible to say in which direction the shortening was greatest; commonly it is assumed to be the horizontal direction normal to a fold axis, even where fold axes plunge. Sometimes it is possible on the basis of fabric symmetry to deduce that movements have not only a horizontal direction (for instance a direction of shortening) but /

but also an overall consistent sense of rotation or translation. However, not all folds denote the presence of an overall constant direction-sense of translation or "transport" normal to their axes. The attitude of axial surfaces can be helpful in determining the overall symmetry of movement that has caused folding. Horizontal squeezing tends to produce folds with vertical axial surfaces whereas rotational strain produces folds with axial surfaces inclined to the horizontal. A vertical squeezing cannot produce folds in a horizontal layering without a preceding phase of horizontal squeezing or shearing.

2. Kinematic analysis is made more complete by mentally or graphically deriving an observed structure from an assumed earlier structure by the minimum amount and simplest possible kind of movement consistent with the movement picture. The "unrolling" (Rückformungen) and "levelling" (Horizontierung) techniques used by Sander (1948, pp. 170-184) to determine the movements by which an initially horizontal and planar sedimentary layering has acquired a folded form are good examples of this procedure. These techniques can be used only on a foliation that is demonstrably parallel to sedimentary bedding; also, the graphical methods of unrolling used are complex and time-consuming and can be used only in a very general fashion by /

by a reconnaissance geologist. One or two simple examples are given below.

Kinematic analyses are necessarily made upon fabrics which show only the last stage of what may have been a long and complex evolutionary history, which, for some fabrics, may have included superposed genetically unrelated phases of deformation. The most important indicator of the nature of deforming movements is statistical symmetry of fabric, which, in a general fashion, can be equated, by way of the principle of symmetry, with symmetry of movement. A movement picture is best constructed in a qualitative fashion on the basis of fabric symmetry. The more quantitative process of reconstructing individual stages in kinematic evolution by unrolling requires important primary assumptions which can be made only after the most detailed investigations of the fabrics concerned.

The problems of dynamic interpretation of structural geometry are even greater. The inference of stresses from movements is far more open to error than is the inference of movements from geometry. Particular difficulty is experienced in distinguishing the effects of rotational stress (a force-couple) from those of non-rotational stress; also, external stresses are generally very different from the internal stresses they produce in a deforming body, and so scale is very important in /

in dynamic analysis. For instance, rotational and non-rotational stress can be equated respectively with shearing and squeezing, but external squeezing of a body of rock commonly produces heterogeneous internal shearing (for instance, flexural slip folding) on surfaces, such as foliation, within it. For this reason, proof of rotational stress on a small scale does not mean necessarily that stress on a large scale also has been rotational. Great caution must be used in drawing dynamic conclusions about deformed rocks even where movements are clear.

Fabric axes: The introduction into this discussion of fabric axes has been delayed because an understanding of the significance and use of these axes in structural analysis is impossible without some knowledge of the different types of symmetry found in deformed rocks. The axes employed by most structural geologists are the orthogonal a-, b(B)- and c-axes initially proposed by Sander (1926, p. 328). No really comprehensive definition of fabric axes for fabrics with differing symmetry exists in the English language, and it is doubtful whether, even today, the full philosophical content of Sander's initial purpose in defining these axes has become apparent to the /

the bulk of English-speaking structural geologists. For this reason, great care must be exercised in using these terms. To continue sprinkling papers with references to a- and b-axes, the significance of which is imperfectly understood by the writers themselves, can lead only to confusion and worthless argument. In Britain and Scandinavia, in particular, futile controversy on the subject of a- and b-lineations in the rocks of the Caledonides has occurred from time to time over a period of years. In the view of the writer this controversy arose out of a lack of appreciation, on the part of the geologists involved, of the importance of the symmetry of fabric in kinematic interpretation, and a confusion of fabric axes with kinematic axes. It is impossible and inappropriate here to examine this controversy in any detail, but a similar problem in interpretation has arisen in the Turoka area, where a regional B-lineation has been interpreted as an a-lineation, and so it is necessary to define and discuss fabric axes.

Fabric axes are used to describe geometry and symmetry of fabric and they correspond, in most fabrics, to an identical set of kinematic axes which describe movements. These axes are defined respectively for (1) fabrics with monoclinic symmetry, and (2) movements with monoclinic symmetry.

The /

The definitions favoured by the writer are as follows (Weiss, 1955, p. 229):

"1. . . . ab is the principal fabric plane. This is the most prominent surface in the fabric, that is, the foliation. The symmetry plane (which, since symmetry is monoclinic, must be normal to ab) is ac, and the normal to the plane of symmetry is b. In many deformed rocks ab is folded with b as fold axis. Since b is therefore a direction of maximum continuity in the fabric it is designated E.

"2. The kinematic axes are defined for rotational strain involving slip upon one s-plane. The slip plane is ab, the deformation plane is ac, and the normal to the plane of deformation is b. The direction of slip is a. Deformation is commonly by flexural slip of ab; and b, as the axis of external rotation, is again a direction of maximum continuity designated E."

From these definitions the following conclusions can be drawn for fabrics with monoclinic symmetry:

1. Foliation invariably contains the E-axis and is normal to the ac-plane. This does not mean necessarily that the foliation is a surface of slip.

2. The axes of flexural slip folds are invariably parallel to the E-axis.

3. /

3. Lineations are either parallel to the B-axis (lineations of types 1, 2 or 3; see pages 275 and 276) or they are parallel to the a-axis (lineations of type 2 only).

The recognition of fabric axes in fabrics with monoclinic symmetry is straightforward. Difficulties appear when attempts are made to recognise the same three axes in fabrics with triclinic symmetry. In the Scottish Highlands (and perhaps also in Scandinavia) it is becoming increasingly obvious that many fields on a large scale have triclinic symmetry. Lineations occur widely with great variety in orientation and degree of regularity. Most of these lineations are, on a small scale, demonstrably B-axes. In spite of this fact, attempts have been made to interpret them as a-lineations in order to fit the lineations into a kinematic interpretation already made on some other grounds. Anderson's (1948) contribution to the problem is concerned not so much with fabric axes as with kinematic axes; but he considers in detail a type of lineation common in the Highlands and elsewhere in bodies of rock deformed by flow which he calls the "Tummel type" of lineation. He interprets this lineation as an a-lineation parallel to a kinematic a-axis, that is, a direction of slip on a single set of slip surfaces. The description of this /

this lineation given by Anderson shows it to be identical to the regional lineation at Turoka; the details are quoted here in full:

- "(a) The lineation of micaceous rocks runs parallel to the direction of elongation (corresponding to the g-axis) of the hornblende crystals in the adjacent hornblende schists.
- (b) It runs with great regularity parallel to the pitch [plunge] of minor folds.
- (c) When the rocks are studied microscopically, and found to be S-tectonites, the lineation is almost always perpendicular to the direction of concentration of the mica poles and quartz axes.
- (d) When the rocks are E-tectonites the lineation is, in the great majority of cases, perpendicular to the planes of the girdles.

"The minor folds referred to under (b) appear to be a world wide phenomenon. They may be anything from an inch or so to hundreds of feet in amplitude, and are distinguished by the persistence with which they maintain a uniform cross-section. The smaller types have been denoted as 'mullions', but the term crenulate folds, used by E. Cloos, is perhaps better, because of the variation in size."

In this passage, Anderson has given an accurate description of a structure with monoclinic symmetry, and there is no doubt that the lineations and other structures he describes are parallel to E-axes as defined above. With this fact there can be no argument. However, Anderson puts forward the view that these lineations are parallel to the "direction of shear", in /

in other words, an a-axis. Although Anderson supports his view by drawing analogies between flow in rocks and "canal flow" in fluids, it seems to the writer that his real reason for considering these to be a-lineations becomes apparent in the following paragraph (p. 101):

"These folds may be large enough to be mappable, but it should not be assumed that they are parallel, in any district, to the main system of folding. The mullion structures of North-West Scotland are well known, and one series of these is found above the Moine Thrust in the Moine schists of Strath Oykell. Here they run west-north-west, while the strike and the main folds, are in a perpendicular direction."

From this passage it is evident that Anderson has extended his field of investigation from the scale of the lineations, mullions and small folds to the scale on which the "main system of folding" becomes apparent. Already in this discussion a warning has been sounded against assuming the presence of an axis of large scale folding parallel to the strike of uniformly dipping layers of deformed rock without first making a geometrical demonstration of its existence. Recent work in the Highlands is at last affording evidence of the existence of folds on a large scale upon which folds on a smaller scale are superposed (Sutton and Watson, 1954) and it is probable that the "main system of folding" envisaged by Anderson exists in certain parts of the Highlands. However, the fundamental objection /

objection to Anderson's view that the lineations and small folds are a -axes does not rest upon the existence or non-existence of large folds with lineations of different trend superposed on the limbs, but upon the fact that Anderson extends his investigation from a small field with obvious monoclinic symmetry to a large field with obvious triclinic symmetry yet still attempts to use the fabric and kinematic axes defined for monoclinic symmetry.

In order to appreciate the significance of fabric axes in fabrics with triclinic symmetry, some features of the deformations which produce these fabrics must be considered. Fabrics with triclinic symmetry are of two main kinds: first, those produced by a single non-plane deformation, and second, those produced by a superposition of two or more unrelated deformations. These will now be considered in that order.

Triclinic fabrics $B \perp B'$: A single triclinic deformation is best envisaged in terms of two synchronous monoclinic deformations in which the deformation planes are mutually perpendicular (Sander, 1948, pp. 73-83). From a regional point of view, most triclinic structures arise in the following way. A body with a planar horizontal layering (figure 11a) can be strained by horizontal squeezing either biaxially or triaxially. If it /

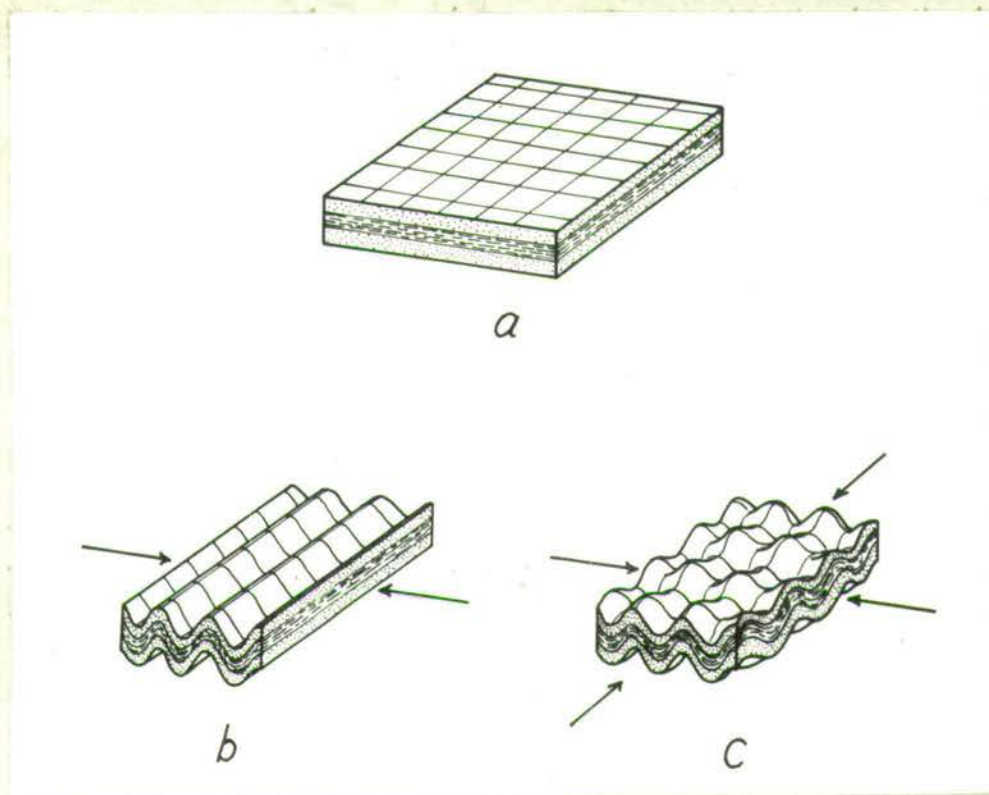


Figure 11. Biaxial and triaxial strain of horizontally layered body.

it is assumed that flow is by slip on \underline{S} , then biaxial strain produces flexural slip folds of \underline{S} and the fabric has monoclinic symmetry (figure 11b). Similar folds together with "cross-folds" are here ascribed to triaxial strain of the same body so that there is a subsidiary axis of shortening normal to the main axis of shortening (cf. Sander, 1948, pp. 180-181), as shown in figure 11c. The movement and the fabric have triclinic symmetry. The relation between the size and form of the interfering folds depends upon a number of factors. In figure 11c they are shown of similar size and form suggesting that the two squeezings are of similar intensity and acted synchronously. But, commonly in rocks, it is observed that the two sets of folds are expressed very differently. Whatever the form of the folds, their axes lie respectively in two mutually perpendicular planes (\underline{B} and \underline{B}' in figure 12). Some possible interrelations in form of the interfering folds are shown diagrammatically in figure 12, as follows:

Figure 12 a; Large folds with axes in \underline{B} ; lineations in \underline{B}' .

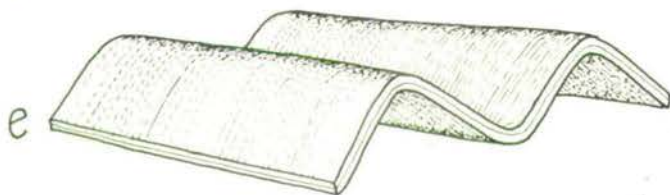
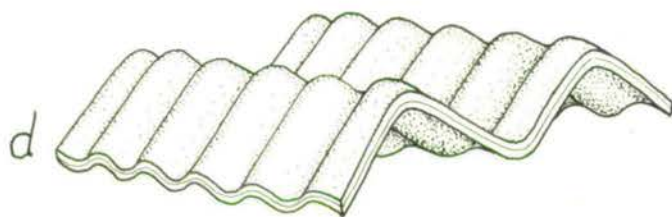
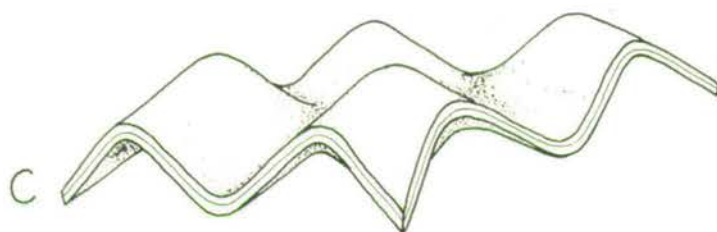
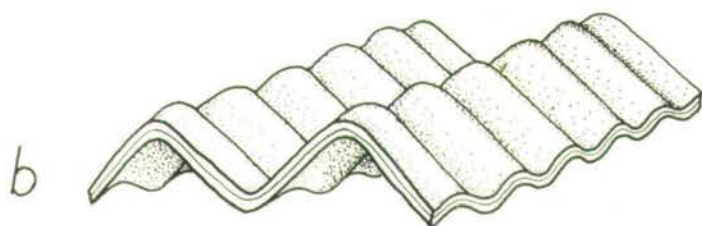
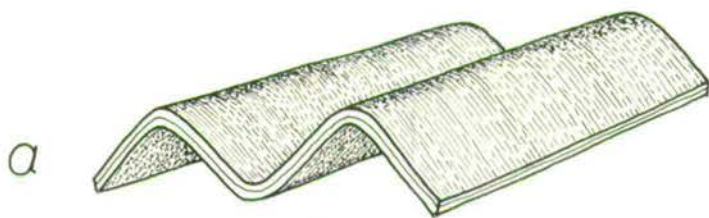
Figure 12 b; Large folds with axes in \underline{B} ; small folds with axes in \underline{B}' .

Figure 12 c; Large folds with axes in \underline{B} ; large folds with axes in \underline{B}' .

Figure 12 d; Small folds with axes in \underline{B} ; large folds with axes in \underline{B}' .

Figure 12 e; Lineations in \underline{B} ; large folds with axes in \underline{B}' .

Figures /



Figures 12a and 12c and figures 12 b and 12 d are geometrically identical.

Generally, one set of folds is much larger and more open than another. Because large folds require relatively great freedom of movement in a vertical direction for their formation, whereas lineations and small scale cylindroidal structures suggest restricted movement under great confining stress, it is probable that the larger folds in triclinic structures are initiated first in a phase of essentially biaxial strain with monoclinic symmetry and the smaller folds are initiated later when strain is markedly triaxial. The two types of fold can continue to form synchronously once their general form is fixed. Whatever may be the size and form of these flexural slip folds their axes are E-axes. Each E-axis is normal to one of the two axes of squeezing and for a planar orientation of S the two E-axes are mutually perpendicular. Statistically, the axes lie in two mutually perpendicular planes as shown in figure 12. In figure 13 is shown a portion of a triclinic structure in which S is planar. Each E-axis is paralleled by a lineation which, in the formation of the triclinic structure, is an axis of rotation in the sense shown. It is possible to define a- and c-axes for each of the monoclinic movements represented by the E-axes. a, E and c are the /

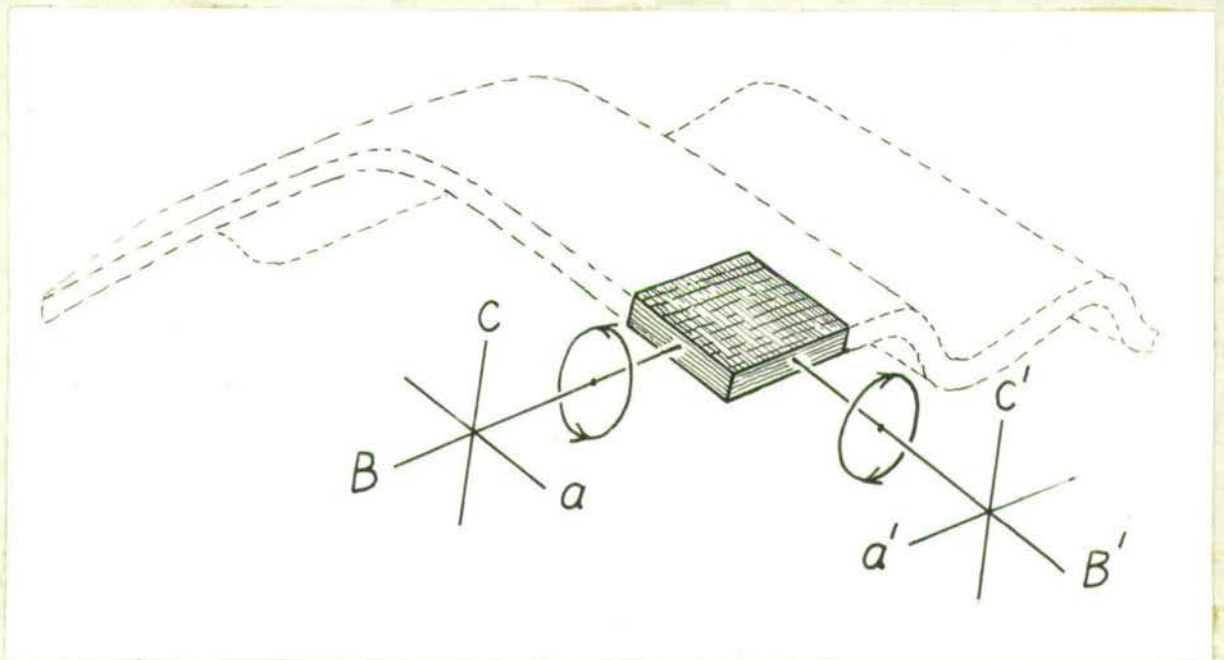


Figure 13. Resolution of triclinic strain into two mutually perpendicular monoclinic strains ($\underline{B} \perp \underline{B}'$).

the kinematic and fabric axes for one phase and $\underline{a'}$, $\underline{B'}$ and $\underline{c'}$ for the other. It can be seen from figure 13 that \underline{a} is parallel to $\underline{B'}$, \underline{B} is parallel to $\underline{a'}$ and \underline{c} is parallel to $\underline{c'}$. The symmetry of the fabric and the movements can be described in terms of the two \underline{B} -axes only. Such a fabric is called a $\underline{B} \perp \underline{B'}$ -tectonite (Sander, 1948, p. 82). There is no fundamental difference on genetic grounds between \underline{B} and $\underline{B'}$ and it is immaterial which axis is labelled \underline{B} and which $\underline{B'}$. Figure 12 is an attempt to show this fact in diagrammatic form. In some rocks one axis is much more prominent than the other. The Swiss Alps, for instance, have an obvious axis of large scale folding that is labelled \underline{B} ; but the depressions and culminations in the plunge of this axis, which probably reflect a degree of triaxial strain, give rise to large, open flexures in the limbs of the Nappes with axes normal to \underline{B} . These may be looked upon as $\underline{B'}$ -flexures. In parts of the Scottish Highlands, one axis is expressed as plunging folds on the limbs of large, open folds. Locally, only this second axis can be detected by geometrical means in a small field. Which of these axes is labelled \underline{B} and which $\underline{B'}$ is not important. Movement parallel to the axes of first formed folds of large size may be less intense and penetrative than the movements that formed the later cross-folds.

Anderson (1948, pp. 120-122) comments upon Sander's view that triclinic movement can be resolved into two syngene-tic monoclinic movements (slip in mutually perpendicular directions on the same slip surface) and suggests that such movements would be expressed in the form of a single oblique monoclinic movement. His view is based upon the assumption that the monoclinic movement involved is a simple shear. This is not so on most scales in deformed rocks. Flexural slip is more important than planar slip when the field of more than one limb of a fold is considered. Fold axes which form parallel to each \underline{E} -axis control the possible directions of slip down to the smallest scale and no resultant slip oblique to \underline{E} and \underline{E}' is possible. Also, Sander points out that the two deformations (about \underline{E} and \underline{E}') are not simultaneous but act alternately in small overlapping phases.

Anderson's picture, in the Scottish Highlands, of large folds with horizontal axes and small folds and lineations superposed parallel to the dip of the limbs suggests a $\underline{E} \perp \underline{E}'$ -structure. Both axes are demonstrably \underline{E} -axes and the symmetry of the whole structure is triclinic and not monoclinic as Anderson seems to suppose. The \underline{a} -axis, as defined for monoclinic symmetry, is not used to describe fabrics with triclinic symmetry. The large folds with horizontal axes envisaged by Anderson /

Anderson in parts of the Highlands have left no penetrative trace of their existence on a small scale either because this trace has been overprinted by the more intense componental movements which produced the plunging E-structures, or because the large folds formed initially without componental movement are are not tectonitic. This is apparent because the field of one dipping sheet of rock, corresponding, according to Anderson, to one planar limb of a large fold, can have monoclinic symmetry on all scales within it and not the triclinic symmetry expected of E \perp E'-tectonites. The only E-axis demonstrable on grounds of symmetry in such a field is that parallel to the plunging folds, mullions and lineations; a dipping sheet does not mean necessarily the presence of a horizontal fold axis parallel to the strike. If a geologist studies such a homogeneous monoclinic field he is required to give a geometrical and kinematic analysis of that field only. The plunging axes represent the direction of minimum structural change within the field considered and in geometrical analysis profiles should be drawn normal to this direction. Examples of the analyses of monoclinic fields within the Highlands have been given by McIntyre (1951, 1952). However, insufficient work has been done in the Highlands to establish whether /

whether, on the scale of the whole deformed body, they are to be considered an area of $\underline{B} \perp \underline{B}'$ -tectonics or of the $\underline{B} \wedge \underline{B}'$ -tectonics now to be described.

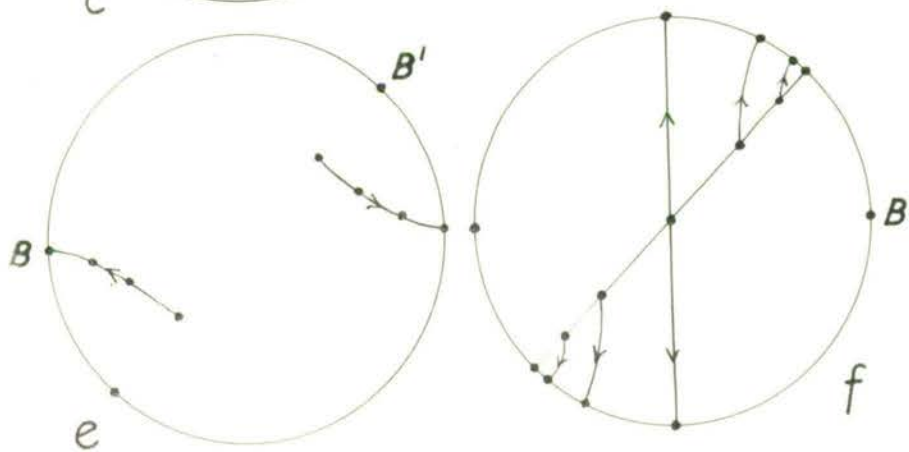
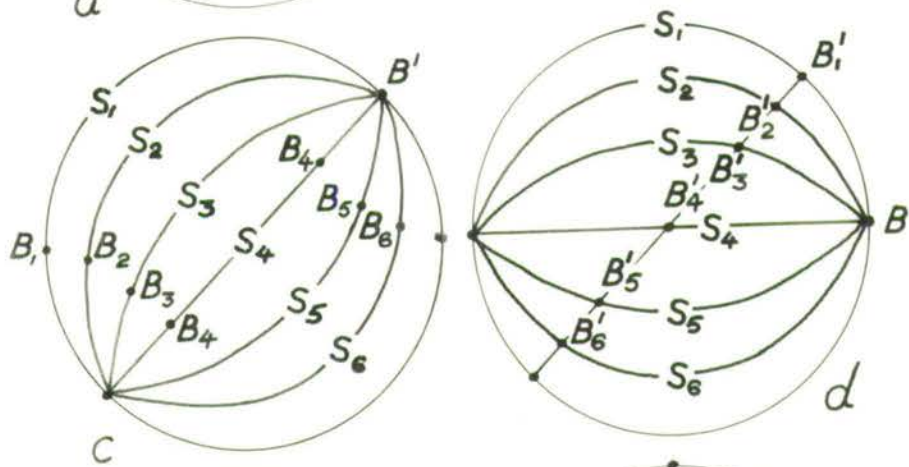
Triclinic fabrics $\underline{B} \perp \underline{B}'$: The fabrics produced by unrelated superposed strains are generally complex and interpretation of such fabrics may lie outside the scope of a reconnaissance geologist: but in order to demonstrate the principle of unrolling and show how Sander distinguishes fabrics produced by superposition of two unrelated monoclinic deformations from these produced by a single non-plane deformation of the kind just described, one or two simple geometrical relations are described.

The simplest cases of superposition of two monoclinic strains best can be demonstrated by considering a body of rock with a planar horizontal layering (\underline{S}) deformed by slip on \underline{S} in two successive unrelated phases by mutually inclined biaxial strains (horizontal squeezings). The first phase of squeezing produces, normal to the direction of squeezing, a \underline{B} -axis expressed as structures of size and form somewhere between lineations and large folds, depending upon tectonic environment and scale of investigation. If the strain is expressed only as a \underline{B} -lineation, then the structure at the end of the first phase /

phase of squeezing is as in figure 14a. \underline{S} is statistically planar and carries \underline{E} as a penetrative imprint. If the second biaxial strain, oblique to the first, is expressed in the same fashion, then a second \underline{E} -lineation (\underline{E}') is formed in \underline{S} at an angle to \underline{E} as shown in figure 14b. However, if the second deformation is expressed as large folds, then \underline{S} becomes folded as in figure 14c ($\underline{S}_1, \underline{S}_2, \underline{S}_3$, and so on) and the lineation \underline{E} occupies positions $\underline{E}_1, \underline{E}_2, \underline{E}_3$ and so on, on respective attitudes of \underline{S} . These positions lie on a small circle of the projection, centre \underline{E}' (Sander, 1948, pp. 171-172).

If the first biaxial strain produces large folds, then \underline{S} becomes folded about \underline{E} ($\underline{S}_1, \underline{S}_2, \underline{S}_3$ and so on in figure 14d). \underline{E} -lineations produced by the second deformation ($\underline{E}_1, \underline{E}_2, \underline{E}_3$ and so on) are superposed upon already formed folds as shown in figure 14d. They lie in a vertical plane normal to the direction of squeezing (\underline{P}') so that each \underline{E}' -lineation is normal to this direction. But the \underline{E}' -lineations on each planar attitude of \underline{S} have different movement planes because the surface of slip (\underline{S}) is inclined differently to the horizontal.

Sander (1948, pp. 174-178) points out that these geometrical relations are a means of distinguishing lineations and /



and small folds superposed on the limbs of a large fold after it has been formed from lineations and small folds already on S before folding. This is done by unrolling S about the axis of folding and levelling it to its initial horizontal and planar orientation. If the attitudes of S in figure 14c are restored to the horizontal by rotation about E', then the lineations (E) come to lie in a single maximum corresponding to the initial trend of the lineation before folding (figure 14e). The folding therefore is demonstrably younger than the lineation. Unrolling of S in figure 14d in a similar fashion does not bring the different positions of E' into a single maximum (figure 14f). The E'-lineations thus were formed after the folding of S. Use of these techniques of unrolling is not straightforward and universally applicable for several reasons of which the most important are as follows:

1. It must be established beyond doubt that the initial orientation of S was planar and horizontal, that is, S is sedimentary layering.

2. It can be seen from figures 14e and f that the differences in orientation respectively of E and E' after unrolling are not great and do in fact grow less as the angle between E and E' approaches 90° (corresponding to successive mutually /

mutually perpendicular biaxial strains).

3. The axes of large folds commonly plunge in a field of investigation and \underline{S} cannot be unrolled about the fold axis into a horizontal orientation.

4. If folds are recumbent, then unrolling and levelling may be carried out in the wrong sense unless initial top and bottom of individual layers can be determined.

5. \underline{E} -lineations superposed on large folds by later movements (figure 14d) become geometrically indistinguishable from $\underline{E} \perp \underline{E}'$ -structures where two superposed biaxial strains are mutually perpendicular (see, for instance, Reynolds and Holmes, 1954). Sander (1948, p. 180) maintains that cross folds produced by triaxial strain generally can be distinguished from those produced by unrelated superposed biaxial strains by the mutual inclination of the \underline{E} -axes. \underline{E} -axes which form as a result of triaxial strain ($\underline{P} \perp \underline{P}'$ in figure 15a) are mutually perpendicular ($\underline{E} \perp \underline{E}'$), whereas, in the general case of superposed unrelated biaxial strains (\underline{P} and \underline{P}' in figure 15b) the \underline{E} -axes which form are mutually oblique ($\underline{E} \wedge \underline{E}'$). These relations must be established statistically.

Conclusions of importance to a reconnaissance geologist which can be drawn from this brief and simplified account of /

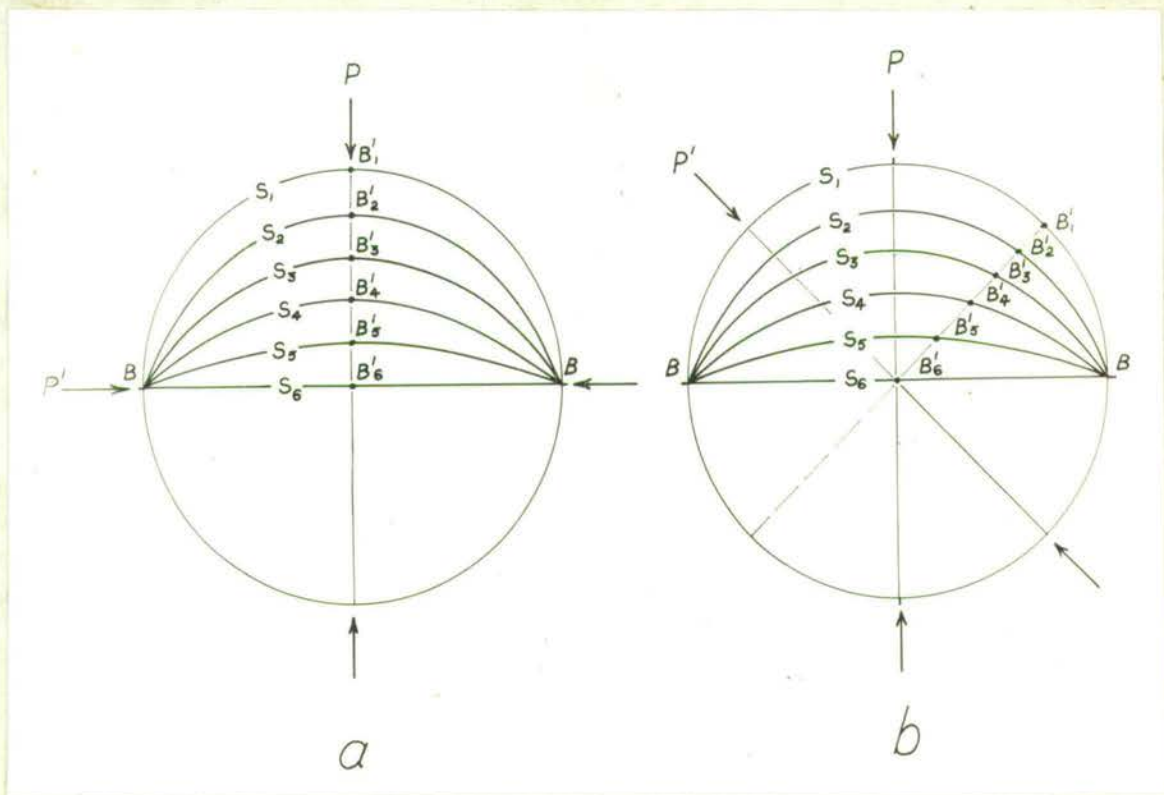


Figure 15. Geometry of $\underline{B} \perp \underline{B}'$ and $\underline{B} \cap \underline{B}'$.

of triclinic structures concern the different ways in which plunging flexural slip folds and E-lineations can arise.

Three main ways can be distinguished:

1. A single triaxial strain can produce E-axes plunging at any angle in initially horizontal slip surfaces. The plunge of the E-axes can change with progressive deformation; in general it steepens.

2. Oblique squeezing of previously folded slip surfaces produces E-axes on the limbs of the folds plunging at angles decided by the direction of squeezing and the attitudes of the limbs. Folds produced on vertical limbs plunge vertically whatever the direction of squeezing.

3. A E-axis may be tilted by later folding after its formation.

Whatever their mode of origin, plunging fold axes and lineations are E-axes if they fulfil the requirements of fabric symmetry. It is not necessary to assume that E-axes can form only with a horizontal orientation or that the axes of all large flexural slip folds are horizontal and parallel to the strike of dipping layers.

Orthorhombic fabrics: Fabrics with orthorhombic symmetry on a small scale are relatively rare in deformed rocks. It is impossible /

impossible to use in these fabrics the same criteria for definition of fabric axes as are used for fabrics with monoclinic and triclinic symmetry because no fabric with orthorhombic symmetry can be produced by slip on foliation. For orthorhombic symmetry to exist, slip surfaces in a fabric must be symmetrically related, in both orientation and sense of slip, to strain axes; no single set of planar slip surfaces can have such a symmetrical relation. The significance of orthorhombic symmetry is beyond the scope of this paper, although some observations on the significance of the orthorhombic patterns of preferred orientation of quartz found in the Taroka area are made below.

IV. STRUCTURAL ANALYSIS IN THE TUROKA AREA

1. Preliminary Statement

Geometrical analysis is a search for statistical structural homogeneity. This may be met with on any scale with respect to any structural element. Geometrical analysis in the Turoka area has been made, to some extent, on all three scales. The procedure followed in the field and laboratory can be summarized as follows:

1. General examination of the whole area to determine the style of the tectonics and the broad degree of regularity in structure.

2. Detailed macroscopic investigation of small homogeneous fields, such as hand specimens and continuous exposures, to establish the nature of the penetrative structures and the highest degree of structural homogeneity to be found within the area.

3. Extension of the investigation to the megascopic scale by examining the degree of variation between macroscopically homogeneous fields.

4. Supplementing of these field investigations in the laboratory by analysis on the microscopic scale of selected specimens.

2. Macroscopic Scale

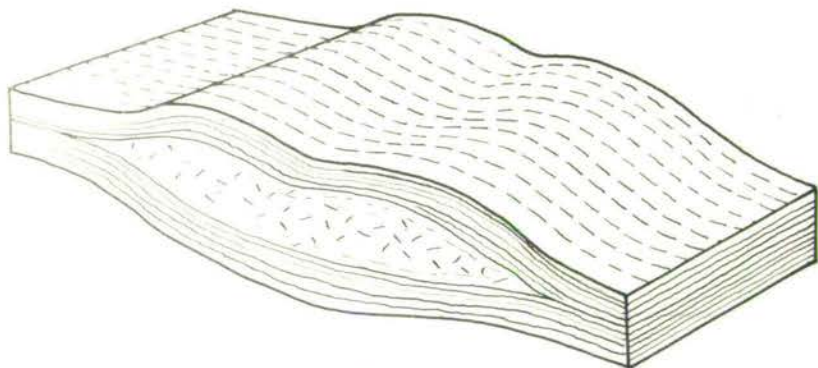
General Statement: The penetrative structures studied in the rocks of Turoka are foliation, folds and lineation. Most specimens show all three, but the nature of the axial structures seems to be more variable than the nature of foliation.

Foliation and folds: Foliation is most pronounced in the micaceous gneisses, but in all rocks, with the exception of the purer layers of marble and quartzite, a visible foliation is to be observed. However, in some strongly lineated and mullioned gneisses, foliation is so subordinate to lineation as to be macroscopically unmeasurable. The foliation is termed S and the following are some of its more important features as determined in individual exposures and hand specimens:

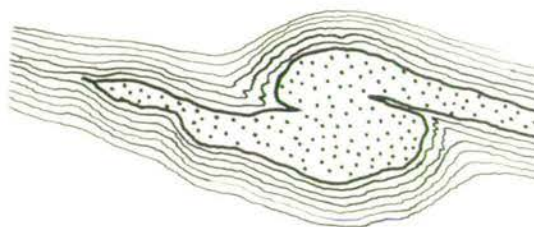
1. Commonly, S is paralleled by layers and lenses of different mineralogical composition. Within the gneisses, layers of biotite and granitoid gneiss alternate with layers of hornblende gneiss and amphibolite. Also, at contacts between rocks of widely differing composition, such as marble and gneiss or gneiss and quartzite, the foliation appears always to be parallel to the contact. In this it superficially resembles /

resembles sedimentary bedding. But, although the rocks have generally a flaggy, bedded appearance (plate 1), close examination shows that much of the layering, on even a small scale, is lensoid. In figure 16a is shown a lens of hornblende gneiss in biotite gneiss. Commonly, such lenses are much more flattened than the one illustrated and only by following individual layers is the lensoid form established.

2. In some places the foliation is also defined by a preferred orientation of platy minerals, especially mica; but in other places the mica flakes are seen in hand specimens to lie with a preferred orientation in a plane oblique to the foliation as defined by differential layering, and, in extreme examples, the mica flakes constitute a second important fabric surface (S_1) which intersects S to form a lineation of type 3. In the localities in which S_1 is prominent, S is found generally to depart from the regional orientation observed by Joubert in Namanga-Bissel area. S_1 is most prominent where S is vertical (figure 16c). Where folds in S can be seen macroscopically, S_1 forms parallel to the axial surfaces of these folds and approaches in orientation the regional attitude of S . On a macroscopic scale, S in incompetent layers is locally to be seen partially or completely transposed by folding into S_1 which, in /

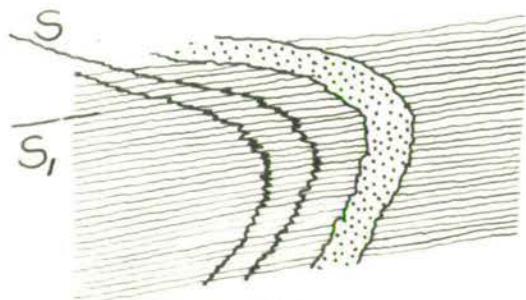


a

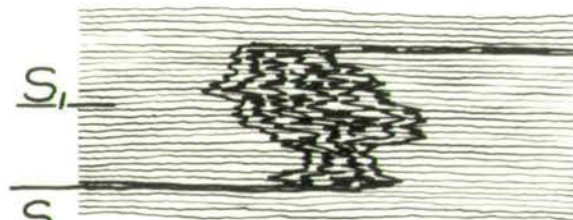


b

ONE
FOOT



c



d

in limit, is paralleled by a crude layering made up of transposed fragments of layers initially parallel to \underline{S} (figure 16d). Also, small folded fragments of competent layers occur as tectonic inclusions floating in conformable foliation which might be either \underline{S} or \underline{S}_1 (figure 16b). The presence of these folds suggests that the foliation which surrounds them has been produced by transposition of an earlier foliation.

3. The marbles and quartzites as a rule are poor in mica and the foliation within these rocks is defined solely by variations in composition. This is especially true of the marbles that can be seen intricately layered with beds of calc-silicates. Even where foliation in these rocks is folded intensely on a macroscopic scale, there is no sign of a foliation parallel to the axial planes of the folds (plate 2). The presence of mica or other platy minerals seems to be necessary, in the rocks of Turoka, for the appearance of an axial plane foliation, and the transposition of one surface into another by folding and shearing. The bedding in marble and, under some conditions, quartzite, quickly becomes a passive structural element after a first phase of flexural slip folding, and, although it later may undergo slip folding, the fate of bedding in a marble generally is to survive a degree of deformation /

deformation which would transpose a foliation in a surrounding gneiss or schist rich in mica (cf. Weiss, 1954, p. 58).

These are the more important macroscopic features of S in the Turoka area and the interpretations placed upon them. Now to be considered is the statistical orientation of S on a macroscopic scale. In hand specimen, the foliation is generally planar and regular. Also, in individual exposures where there is no obvious folding, measurement and plotting of the poles of S shows that there is a high degree of statistical homogeneity with respect to the orientation of S. In figure 17 and 18 the large dots are Π -poles (S). Figure 17a shows the Π -poles measured in a large tor of granulitic gneiss in the south of the area; figure 17b shows measurements from a similar tor of granulitic gneiss about three quarters of a mile west of the first. The diagrams essentially are identical and the homogeneity with respect to the orientation of S, in this part of the Turoka area, can be extended well beyond the scale of a single exposure. Figure 17c shows Π -poles from a large crag of quartzite on the southern summit of the part of the Lemilebbu Hills within the area. The statistical maximum of Π S occurs in the same place as in the last two diagrams; on the other hand, figure 17d, from an exposure between these last two, shows a slight but distinct change in the /

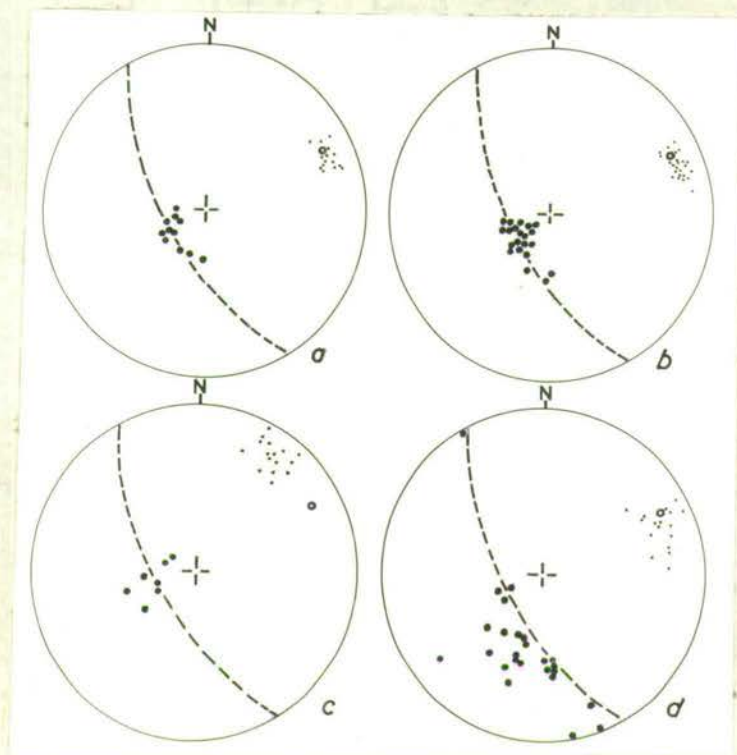


Figure 17. Partial diagrams from the Turoka area (macroscopic scale); large dots, π -poles; small dots, lineations.

the position of the Π -pole maximum. Figure 18b, from a small exposure on southern closure of the Turoka marble, shows a maximum of Π -poles denoting a foliation striking normal to the regional strike and dipping vertically. Thus, the whole of the Turoka area is not macroscopically homogeneous with respect to the orientation of \underline{S} although most measurements of Π -poles fall into a maximum corresponding to the north-north-west strike and shallow easterly dip observed by Joubert. The foliation appears to be folded in some fashion on a megascopic scale. This is to be expected because folds on a macroscopic scale are plentiful. They vary in size and form even on this scale, but there are features of style common to most of them, as follows:

1. The limbs are closely appressed and the hinges are sharp (plates 2 and 3).
2. The axial surfaces of the folds are planar and of very low inclination to the horizontal (plates 2 and 3). Generally they strike north-north-west and dip shallowly eastward.
3. Where exposed for any distance in the direction of the fold axes, the folds maintain very uniform profiles and, on the macroscopic scale, are cylindroidal.
4. /

4. Folds of competent layers in a less competent matrix (for instance, layers of feldspathic gneiss in biotite gneiss) sometimes are rootless and surrounded by gneiss with a concordant foliation: they are "fish" or tectonic inclusions (McIntyre, 1951, p. 5).

5. Where in the gneisses a second visible fabric surface (S_1) is associated with folding, it is invariably parallel to the axial planes of the folds, and it intersects the main foliation (S) producing a lineation or, where development of S_1 is extreme at fold hinges, mullions and rods. In such places the foliation becomes macroscopically obscure and the structure of the rock fibrous.

6. Wherever lineations (of type 1, 2 or 3) are developed in association with folds, they are invariably parallel to the fold axes.

The cylindroidal nature of the folds and the parallelism of lineations with fold axes define monoclinic symmetry for penetrative structures on a macroscopic scale. It is not only the relatively simple folds in marble, uncomplicated by secondary foliation, which have monoclinic symmetry, the folds with axial plane foliation also are monoclinic structures because the intersections of all fabric surfaces coincide with all linear structures. Also, it is apparent that no fundamental /

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PLATES, MAPS and PROFILES

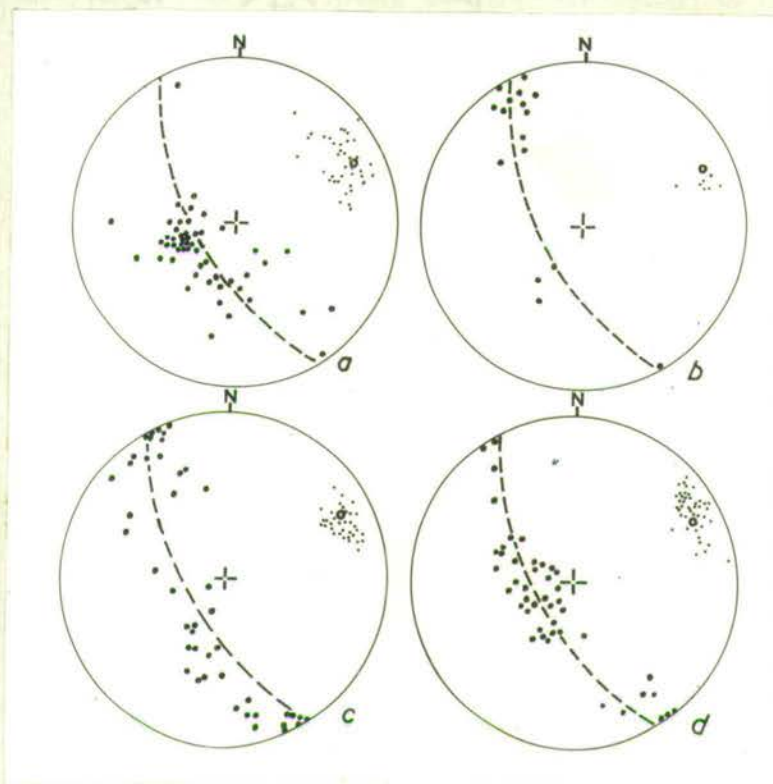


Figure 18. Partial diagrams from the Turoka area (megascopic scale); large dots, Π -poles; small dots, lineations.

fundamental geometrical distinction need be drawn between \underline{S} and \underline{S}_1 in places where they occur together. One is produced by transposition of the other and it is by no means certain in the areas where a single uniform foliation is present in the mica-gneisses whether this is \underline{S} or \underline{S}_1 . It is probable that in some parts of the area the main foliation is \underline{S} in others \underline{S}_1 . Only in the marbles and possibly the quartzites is it likely that the foliation is genetically always the same surface and is invariably parallel to sedimentary bedding. Elsewhere, especially in the micaceous gneisses, the foliation must be looked upon as a structure in kinematic equilibrium during deformation; a structure continually being formed, folded, transposed and reformed during progressive deformation.

On the macroscopic scale no evidence was found for the existence of folds with horizontal axes trending north-north-west of the kind envisaged by Joubert. Two other kinds of fold structure with irregular orientation were observed, as follows:

1. Irregular weak flexures, commonly basin-shaped, occur affecting both foliation and small folds. Some of these flexures undoubtedly were formed late in the tectonic history of the area in a heterogeneous and discontinuous fashion.
- Some /

Some are demonstrably associated with small faults. Others are not true folds but are a product of the lensoid character of the foliation. The upper surface of the structure shown in figure 16a is an example of one of these "folds" in biotite gneiss, caused by a lensoid tectonic inclusion of amphibolite. Such structures occur on all scales, and their structural significance can be evaluated satisfactorily only by statistical analysis on a megascopic scale.

2. Some of the discordant pegmatites are visibly folded in a more or less regular fashion about axes which, although macroscopically regular, vary in orientation from exposure to exposure and are not parallel to the axes of folds of similar style in the foliation of the gneisses. These folds are of particular interest, not from a regional point of view, but because they furnish unusual examples of slip folds with apparent monoclinic symmetry which have, in fact, triclinic symmetry and axes which are not E-axes. One such fold is shown diagrammatically in figure 19. The discordant pegmatite is parallel to a surface S' folded about an axis L' which is the axis of intersection of S' with the foliation (S) in the surrounding gneiss. In S is a strong lineation (L) oblique to L' but parallel to small folds observed in S. This axis (L) is /

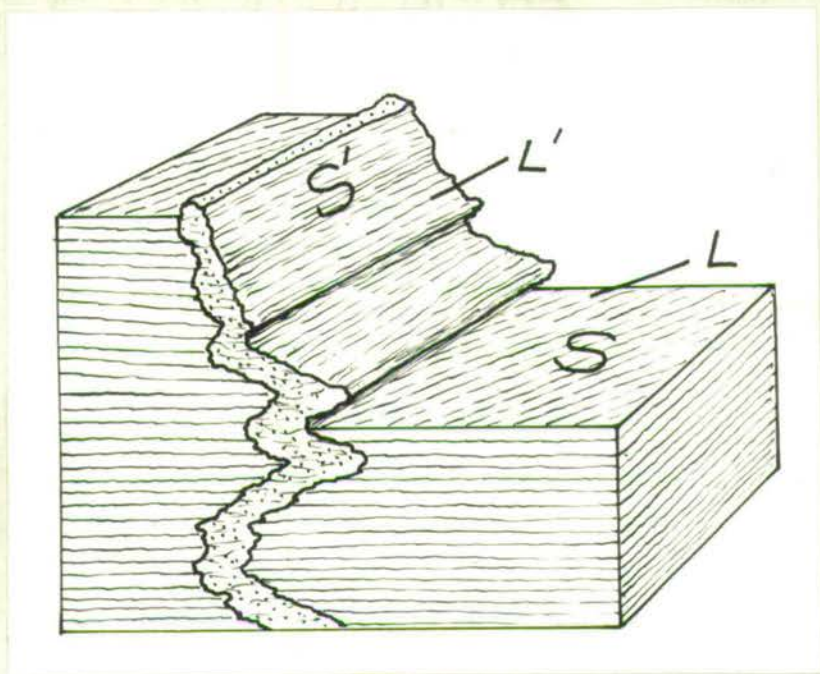


Figure 19. Slip folded pegmatite.

is the \underline{E} -axis for the gneiss, the symmetry of which is monoclinic. If \underline{S}' is assumed initially to have been a planar sheet (many such pegmatites in other parts of the area still are), then folding of \underline{S}' must have been produced by non-affine slip on \underline{S} . This view is supported by the presence in the pegmatite of a crude foliation parallel to \underline{S} . But the axis of slip (\underline{E} -axis) in \underline{S} is given by the lineation \underline{L} , and not by the axis of the folds in \underline{S}' . \underline{S}' was a passive structure during non-affine slip on \underline{S} and was internally rotated (see, for instance, Borg and Turner, 1953, figure 3). Although movement was monoclinic the fabric of the pegmatite is triclinic because \underline{S}' was passive during deformation.

Lineation: Most foliation surfaces in the gneisses have a strong lineation. This generally is expressed in the form of a fine regular ribbing (plate 4); but it varies in character between, at one extreme, an almost imperceptible striation, and, at the other, a coarse mullioning. Most commonly it is defined by an elongation of mineral grains, especially hornblende in the hornblendic gneisses and amphibolites, and by streaky tracts of feldspar and mica in the feldspathic and biotite gneisses (lineation of type 2); in places it is an intersection of fabric surfaces (\underline{S} and \underline{S}_1) and, less commonly, a microfolding of \underline{S} (respectively lineations of types 3 and 1).

The orientation of the lineation (small dots in figures 17 and 18) is macroscopically homogeneous in most exposures and, within certain limits, from exposure to exposure. The greatest variation between individually homogeneous fields to be found in the whole area is shown in figures 17c and 17d. Because the axes of all observed macroscopic folds are parallel to lineation, no amount of such folding can change the orientation of the lineation. The slight variations observed in individual exposures probably are caused by the same phenomena as cause the local variations in the orientation of S, mentioned above.

The regional lineation of the Turoka area is undoubtedly the one observed by Joubert, in the Namanga-Bissel area, with constant easterly trend and shallow plunge

Joints: Joints in deformed rocks are not always to be correlated with penetrative structures because they can be formed by elastic strain leading to rupture without a preceding phase of flow. But the elastic strain stored in a rock after a phase of flow generally is expressed in the form of joints which show a geometrical relation to the structures produced by flow. Two types of joint system most commonly occur in rocks deformed by flow and both are represented in the the rocks of Turoka, as follows:

1. The most commonly occurring joints in the area are oblique or (hkO) joints which are symmetrically intersected by the lineation and stand normal to the foliation (plate 5). The acute angle between the joints usually is bisected by the lineation but in many places the joints are nearly mutually perpendicular. The symmetry of these joints agrees statistically with that of the penetrative structures and, although they formed later, the joints are genetically connected with the flow structures.

2. Joints normal or subnormal to lineation and fold axes occur either in place of or together with oblique joints. Such joints are called ac-joints. They occur most frequently in association with folds, whereas oblique joints tend to occur where S is unfolded. This is only a very general rule to which there are many exceptions. Where they occur in folded rocks, ac-joints have the orientation of a true profile normal to a fold axis, and they provide surfaces ideally oriented for the study of fold forms (plates 1, 2 and 6). The symmetry of the ac-joints agrees within statistical limits with the symmetry of the penetrative structures, with which the joints must share a common origin.

Other joints are developed locally with a variety of orientations.

Homogeneity /

Homogeneity and symmetry: On the macroscopic scale there is throughout the area almost complete homogeneity with respect to the orientation of fold axes and lineations. These structures have monoclinic symmetry and the axes they define is a B-axis. Throughout much of the area there is macroscopic homogeneity with respect to the orientation of S but in certain areas megascopic folding destroys this. The macroscopic symmetry of the fabric is orthorhombic where the foliation is flaggy and unfolded and monoclinic where small folds or two intersecting foliations occur.

3. Megascopic Scale

General statement: The general distribution of rock types within the area already has been described. Of particular interest is the ring-shaped outcrop of marble at Turoka and the crescent-shaped outcrop of marble in the south of the area with anomalous strike normal to the regional mean. The megascopic structures can be represented three-dimensionally in the three ways outlines in the section on structural geometry, as follows:

1. Maps 2 and 3 are structural maps of the area showing the orientation and disposition of the penetrative structures.

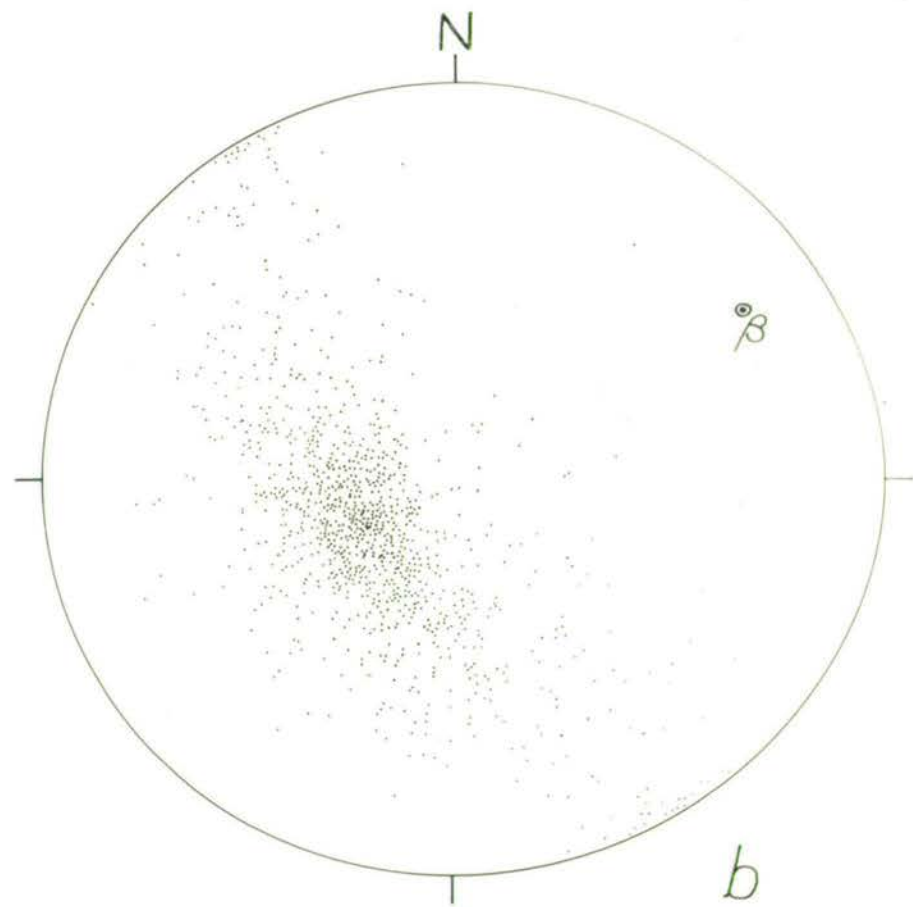
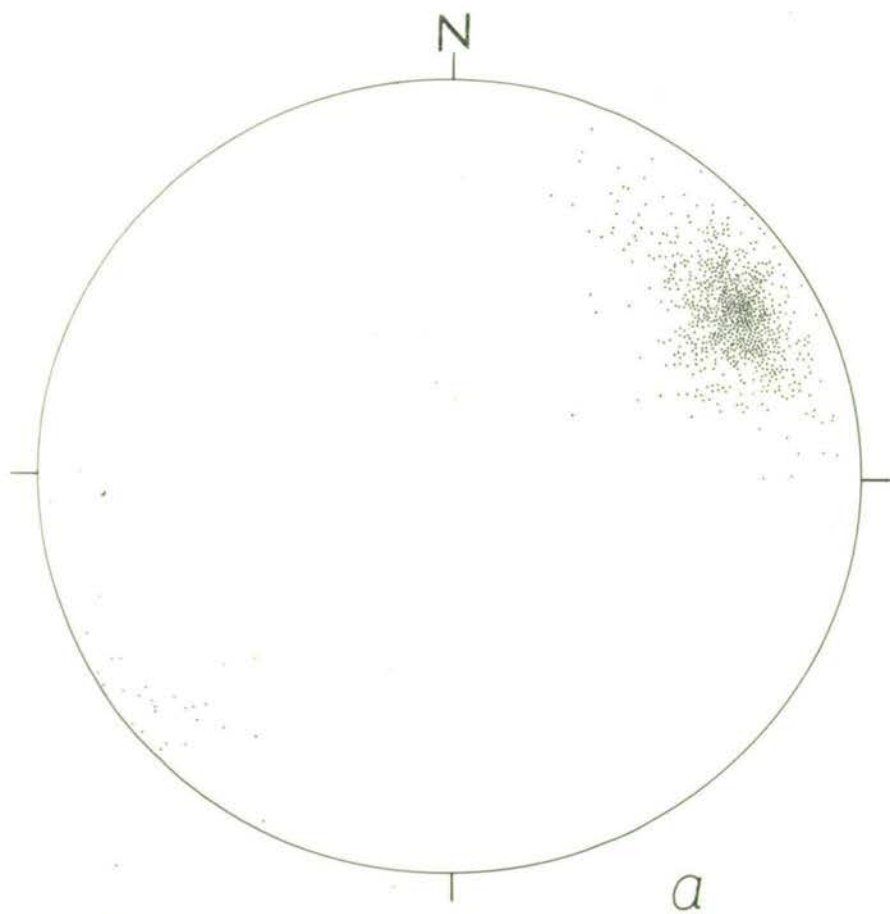
Map /

Map 2 shows the more important lithological boundaries and the trend and plunge of macroscopic folds and lineations. Most of the plotted measurements are averages calculated from numerous readings made on individual exposures. In this way, individual measurements were evaluated statistically and variations caused by local insignificant irregularities in structure were eliminated. The same procedure was adopted with the foliation measurements shown in map 3. In this map, the traces on the ground surface of form-surfaces in the gneiss are sketched in by hand in order to convey to an observer a stronger impression of the geometry of the surfaces defined by the measurements of dip and strike shown on the map. The maps otherwise are self explanatory.

2 and 3. In the next section the results of statistical analysis of penetrative structures from the whole area are discussed and in the following section these results are used in the construction of tectonic profiles.

Statistical analysis of penetrative structures: Investigations on a macroscopic scale show that there is throughout the area a high degree of homogeneity in the orientation of foliation, fold axes and lineations. By combining measurements made macroscopically into synoptic diagrams for larger areas /

areas, it is possible to establish the decrease in homogeneity with increase in scale. For instance, figure 18a shows measurements from the whole eastern limb of the Turoka fold. The degree of homogeneity of the lineations is high but the Π -poles show a definite tendency to spread from a central maximum. Figure 18b shows measurements plotted from a much smaller area at the southern closure of the marble. The degree of homogeneity shown by this diagram has already been commented upon, but the orientation of Π -poles is markedly different from that in figure 18a. Figure 18c shows measurement made along the crescentic outcrop of marble in the south of the area. Again, the linear structures have strikingly uniform orientation, whereas the Π -poles lie not in a maximum but in a well marked girdle about the maximum of linear structures. The foliation on this ridge thus is folded in the same fashion on the megascopic scale as on the macroscopic scale. Likewise, in the gneisses of the south-west part of the area, where folding is strong and two foliations commonly are developed, the Π -poles of both foliations (\underline{S} and \underline{S}_1) lie in a girdle about a strong maximum of linear structures (figure 18d). The degree of homogeneity as expressed in figures 17 and 18 is so striking that synoptic diagrams (figures 20a and b) have been prepared showing respectively the orientation of all axial structures /



structures (lineations and small folds) and of all Π -poles (\underline{S} and \underline{S}_1) measured in the area shown in maps 2 and 3. The synoptic diagram for linear structures shows a single strong maximum defining a regional axis trending north 62° east and plunging 20° to the east-north-east. This corresponds to the trend and plunge of regional lineation observed by Joubert (1956, M.S. in press) in the Namanga-Bissel area to the south, but not to the regional fold axis which he suggested. Further, in order to fit in with his interpretation of the large scale structures, this lineation had to be parallel to a direction of slip on \underline{S} , that is, it had to be an \underline{a} -lineation. But on grounds of symmetry it is demonstrably a \underline{B} -lineation and is not parallel to a direction of simple translative slip.

The Π -poles are arranged in a girdle about $\underline{\beta}$ in figure 20b which coincides with the maximum in figure 20a. This axis is the regional fold axis on both the macroscopic and megascopic scales. Within the girdle is a single very strong maximum elongated slightly in the plane of the girdle. This maximum defines a regional preferred orientation for the collation corresponding to the regional dip and strike observed by Joubert in the Namanga-Bissel area. The position of $\underline{\beta}$ (small open circle) and the Π -girdle are shown on figures /

figures 17 and 18 to show the variation from the regional mean of each partial diagram.

Within the Turoka area, the β -axis defined in these diagrams is the only statistically recognizable axis of folding. There is no sign of a horizontal axes trending north-north-west. But it must be remembered that this demonstration holds only for the field (the area shown in maps 2 and 3) considered.

From the symmetry of the two synoptic diagrams (figures 20a and b) it is possible to deduce certain facts about the megascopic symmetry of fabric and deformation and about the geometry of megascopic folds. Figure 20a shows that the folds are cylindroidal on a megascopic scale. The fold axis therefore is a direction of minimum structural change (statistically, there is no change) and the form of the folds can be represented on a plane surface (the plane of symmetry normal to the fold axis) by construction of a cross section or profile. From figure 20b the following qualitative features of the megascopic folds can be deduced:

1. The folds are recumbent (given by the position of the maximum).

2. The limbs of the folds are closely appressed (given by the single relatively compact maximum).

3. /

3. The hinges of the folds are sharp and the limbs along (given by the greater frequency of measurements corresponding to the limbs than measurements corresponding to the hinges).

4. The axial surfaces of the folds intersect the horizontal along a line normal to the trend of the fold axes (given by the bisector of the maximum, which can be considered to represent the pole of the regional axial plane).

That these predictions agree broadly with features of observed macroscopic folds can be verified by a glance at plates 2 and 3. Further information about the form of particular megascopic folds is given below in the constructed profiles.

Tectonic profiles: A planar cross-section or profile drawn normal to the regional fold axes shows accurately the form of the megascopic structures. To draw a vertical section is of little value because it is a section cut obliquely to the plunging fold axis, showing a distorted picture of the fold forms. Wegmann (1929, p. 107) calls a profile drawn normal to the fold axis a transverse profile and one drawn parallel to a fold axis a longitudinal profile. The first shows the true form of cylindroidal structures, the second does not show the form at all. Profiles parallel to all other planes show /

show the form distorted to a lesser or greater degree. As a vertical section shows a distorted picture of the form of plunging cylindroidal structures, so also (neglecting the effects of topography) does the plane surface of a geological map. Figure 21 is a simple demonstration of this fact. In figure 21a is shown an inclined cylinder intersecting a plane horizontal surface as an elliptical trace (figure 21b). In order to see the true form of the cylinder it must be intersected by a surface normal to its axis (figure 21c) on which the trace of the cylinder is a circle (figure 21d). A cylindroidal structure in a body of deformed rock possesses geometrical features similar to those of a cylinder. The trace of the form-surface of a cylindroidal structure on a map is a distortion of the trace as seen on a transverse profile in the same fashion as the ellipse in figure 21b is a distortion of the circle in figure 21d. Obviously, if the ellipse in figure 21b is viewed orthographically parallel to the axis of the cylinder it is seen as a circle. In the same fashion, if the distorted fold forms on the map are viewed orthographically parallel to the fold axis they are seen in transverse profile. This viewing can be carried out visually, because the eye sees almost in orthographic projection; but a graphical construction can be made to distort a map into a transverse /

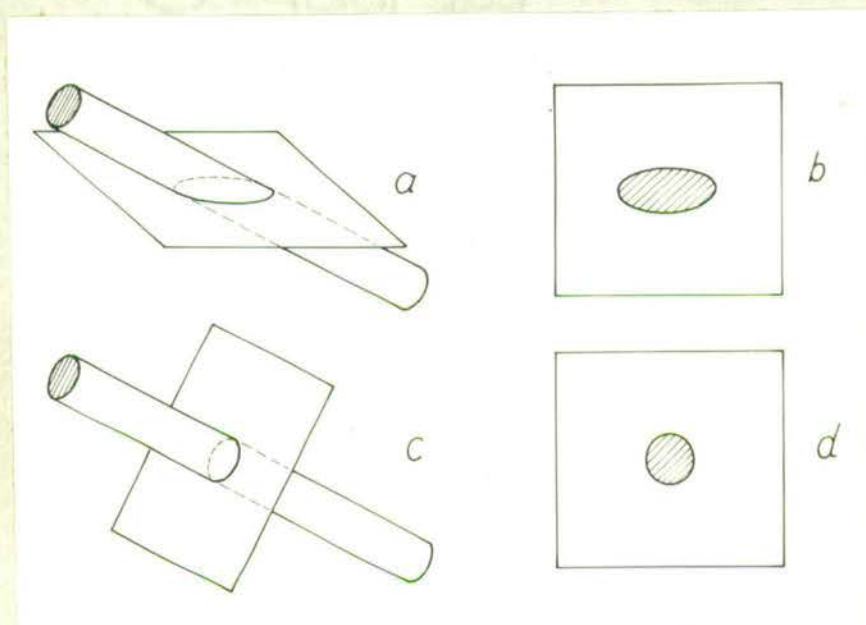


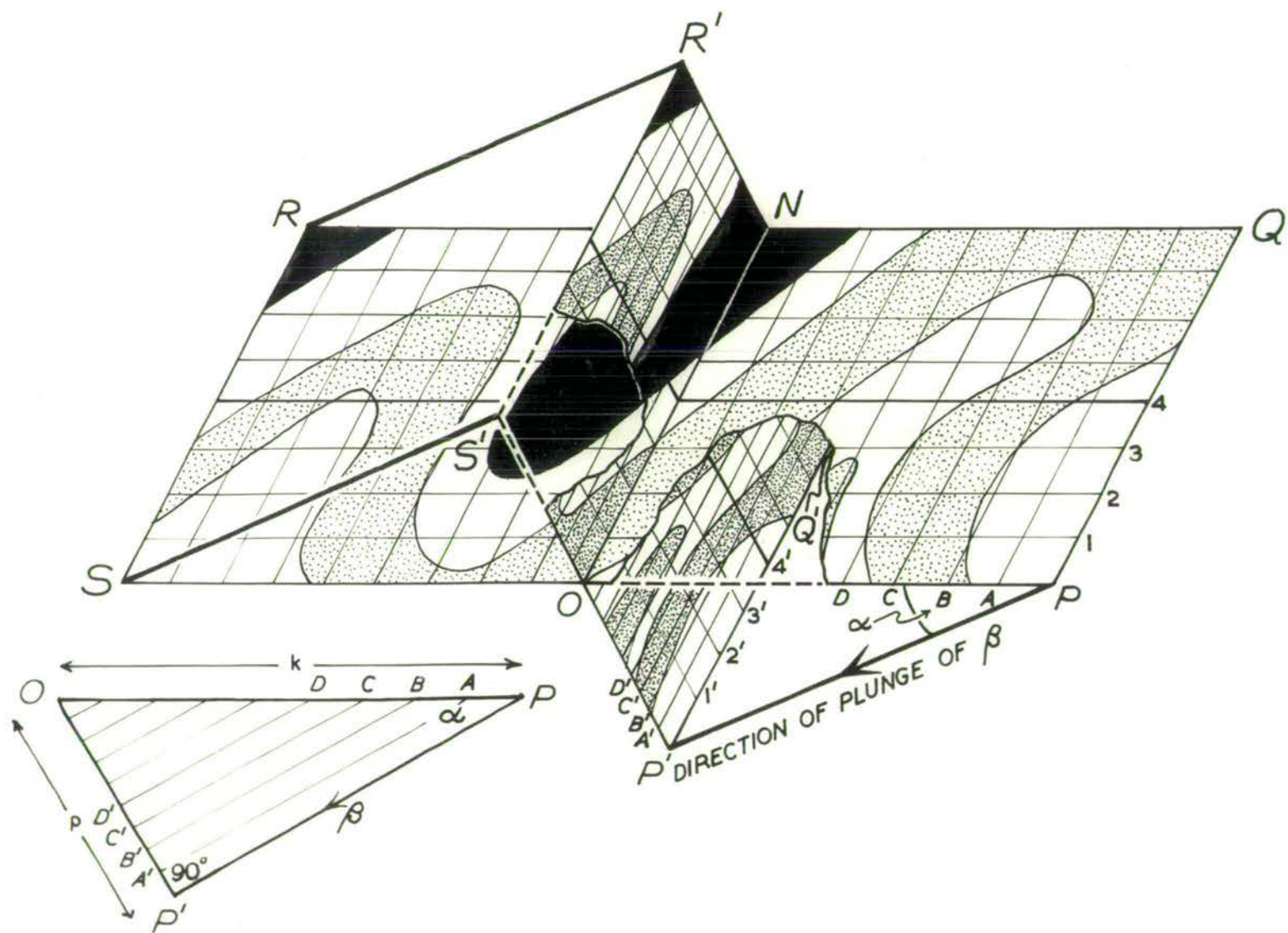
Figure 21. Diagram illustrating geometry of transverse profile.

transverse profile. The geometry of the construction is shown diagrammatically for a hypothetical map and axial plunge in figure 22. PQRS is a map showing lithological boundaries folded cylindroidally about an axis. This axis, parallel to PP', thus is the direction along which the boundaries on the map must be orthographically projected to produce a profile. For convenience, the plane of profile (normal to PP') is envisaged as intersecting the map along the line ON. Each point on the map to the left of ON is projected upwards along lines parallel to PP' to intersect the plane of profile. The four corners of the map project as shown P to P', Q to Q', R to R' and S to S'. A rectangular grid drawn on the map so that one coordinate is parallel to the trend of the fold axis is projected as shown. One set of intervals of this grid (P to 1, 1 to 2, 2 to 3 and so on) remains undistorted after projection, whereas the other set (P to A, A to B, B to C and so on) is shortened on the profile. The degree of shortening can be calculated from the triangle POP' as shown. If the intervals before projection are represented by k , after projection by p and the angle of plunge by α ,

$$\text{then } k \sin \alpha = p.$$

With the calculated value of p , a grid can easily be drawn which /

Figure 22. Construction of transverse profile by axial projection of a geological map (explanation in text).



which represents the grid on the map distorted as it would appear on a transverse profile. The boundaries from the map then can be transferred to the new grid to complete the profile. This construction is that outlined by Wegmann (1929).

The importance of this method of profile construction is that no line appears on the profile which does not appear also on the map. In other words, no speculation is used in its preparation. This contrasts with the method commonly employed in the construction of vertical structural sections in which form-surfaces intersecting the line of section on a map are projected down dip, as long or short a distance as the fancy of a particular geologist dictates, to produce fold-forms which may or may not exist. Projection must be used in construction of profiles, but projection should be made always in the direction of minimum structural change (the fold axis in a cylindroidal structure) and not in a direction of great or maximum change (the direction of dip in surfaces folded about horizontal or shallowly plunging axes). One criticism often levelled at transverse profiles is that the shape of folds may change radically below ground. As Wegmann (1929, p. 108) points out, this objection is insubstantial if the projection is made in an area statistically homogeneous with respect to a /

a fold axis. It is obvious that even in such an area a profile would not be exactly the same in detail if it could be constructed for rocks below the ground surface; tectonic inclusions can and do die out even in the direction of plunge; folds can change their form along their axes - antiforms can turn into synforms and vice versa. But such variations do not affect the overall qualitative features of geometry which is called by Lugeon the tectonic style of the structures. It is in acquiring a feeling for tectonic style that the concept of a form-surface, independent of lithology and stratigraphical detail, is most useful to a geologist. A transverse profile constructed in the manner outlined assists an observer in obtaining a three dimensional view of the geometry of a given body. If it is remembered that a profile does not correspond in detail to any one plane surface in the deformed body and is qualitative rather than quantitative, and if it is further remembered that it is valid only for the field of the map concerned, then such a construction is legitimate and completely defensible - far more defensible than most vertical structural cross-sections which give a wholly subjective view of structure independent of geometrical construction.

In most large bodies with triclinic symmetry no significant /

significant planar profiles of any sort can be constructed because there is not a direction of no structural change. Any representation of a form-surface on a plane surface cut through such a body is an irregular distortion. But if the triclinic symmetry is slight and apparent only on a large scale, then sometimes it is possible to construct profiles for small homogeneous fields with monoclinic symmetry and to combine them artificially on a single plane surface (see, for instance, Lugeon, 1930).

Two transverse profiles of the Turoka area have been constructed. Profile 1 is a transverse profile in which minor corrections have been made to neutralize the effects of topography. Profile 2 is a series of coulisse profiles (Wegmann, 1929), that is, individual transverse profiles drawn across map 2 from a to a', b to b', c to c' and so, showing the topographical profile along each line. The three dimensional effect of coulisse profiles is more striking than that of a simple transverse profile. The plane of projection throughout strikes north 28° west and dips 70° west.

From a study of the profiles the following structural conclusions can be drawn:

1. The Turoka fold is a flattened cylindrical body of marble floating in gneiss. Within the cylinder is an isolated body /

body of marble embedded in the gneiss of the core. Although this body is shown in the profiles isolated from the Turoka fold, it is possible that the two are joined underground along the E-axis. Whether or not the two join or die out does not affect the tectonic style of the Turoka fold as expressed in the profile.

2. The foliation (S) in the gneisses enclosing the Turoka fold is conformable to the outline of the fold. Around the northern closure of the fold, the foliation in the gneisses also closes. However, around the southern closure S does not appear to close in harmony with the foliation in the marble, although this is not certain because of poor exposure in critical localities. As far as can be determined by mapping, S on opposite sides of the fold comes together with no intervening marble and continues uniformly southwards as the regional foliation. The Turoka fold apparently is rootless and the features of the surrounding gneissic foliation suggest that it once rooted towards the south.

3. The Turoka marble once could have been contiguous with the crescentic body of marble floating in gneiss in the southern part of the area. It was the unusual structural features of this marble which initially led to the investigation /

investigation at Turoka. The reason for the unusual features displayed by this body on the map becomes apparent on the profiles. Although internally it is intensely folded, the marble has a fairly regular outline cutting across the regional foliation. The boundaries of the body are essentially vertical and strike on the map parallel to the axial trend. Because the other folds in the area are recumbent, this trend is normal to the regional strike. The outcrop of marble with steeply dipping foliation striking normal to the regional foliation in the gneisses is thus in no way anomalous. The body of marble has the appearance of a partially transposed fold of great size. This view is supported by the fact that the secondary foliation (S_1) of the south-western part of the area projects onto the profile parallel to the axial plane of this fold.

4. The marble and quartzite of the northern spur of the Lemilebbu Hills is probably part of another great tectonic inclusion floating in gneiss. It is possible that this body is a closely appressed fold of quartzite around a core of marble; but poor exposure in the vicinity of the supposed closure makes this interpretation a matter of speculation.

5. The tectonic style, as expressed in these profiles, shows /

shows that attempts to determine the structural geometry of the body by stratigraphical means are unlikely to be successful. The individual outcrops of marble and quartzite within the area are all, as far as can be determined, rootless inclusions of roughly lensoid form embedded in gneiss which has been pervaded by intense movement. To join up individual exposures of, say, marble, into discrete layers on a map is a gross oversimplification of geometry that can lead to a misunderstanding of the large scale tectonics.

6. The coulisse profiles demonstrate which outcrops on the map owe their form to the effects of topography. The apparently small closed bodies of marble on the Lemilebbu Hills are seen to be inliers caused by erosion through an overlying sheet of quartzite. Also, a circular pattern in the gneissic foliation just to the west of the Turoka fold is seen to be a result of irregular erosion through a small antiform.

4. Microscopic scale

General statement6: Study of microscopic structures was made in ten specimens selected from the localities shown in map 4. The following are brief descriptions of the macroscopic /

macroscopic and microscopic structural features of the specimens important from a structural point of view:

128: quartzite; weak foliation defined by scattered grains of feldspar and mica; strong lineation defined by elongated tracts of feldspar and mica; quartz occurs in equidimensional grains with interlocking boundaries, enclosing small grains of feldspar and mica; postkinematic crystallization.

152: quartzite; very weak foliation defined by indistinct colour-layering; strong lineation defined by elongated tracts of feldspar and diopside; quartz occurs in large equidimensional grains with interlocking boundaries enclosing fragments of feldspar and diopside; postkinematic crystallization.

378: quartzite; very weak foliation defined by crude layering of tiny fragments of feldspar, mica, diopside and calcite; no lineation; quartz occurs in large equidimensional grains with interlocking boundaries enclosing tiny fragments of other minerals; postkinematic crystallization.

530: micaceous quartzite; foliation defined by layers rich in mica and feldspar; weak lineation defined by elongated tracts of mineral fragments; quartz occurs in equidimensional grains with interlocking boundaries enclosing tiny grains of mica and feldspar; postkinematic crystallization.

674: quartzite; weak foliation defined by layers richer respectively in mica and feldspar; impersistent lineation defined by ribbing on certain surfaces; quartz occurs in large equidimensional grains with interlocking boundaries enclosing grains of feldspar; postkinematic crystallization.

100: granulitic gneiss; weak foliation impersistently defined by surfaces of easy fracture; lineation defined by elongated tracts of quartz, feldspar and mica; quartz occurs in granulitic form (long flattened lenticles composed of slightly elongated grains) enclosing small grains of feldspar and mica; postkinematic crystallization.

102: granulitic gneiss with same features as 100, but with no lineation.

403: granulitic gneiss with same features as 100.

112: biotite gneiss; strong foliation defined by alternate layers respectively richer in mica and feldspar, and by preferred orientation of mica flakes; faint lineation defined by tracts of feldspar and mica; quartz in small equidimensional grains enclosing tiny fragments of feldspar and mica; postkinematic crystallization.

190: feldspathic gneiss; crude foliation visible as a colour-layering; no lineation; quartz occurs in small equidimensional /

equidimensional grains interstitial to the feldspar: post-kinematic crystallization.

These specimens, although they range from almost pure quartzite to feldspathic gneiss, exhibit certain features in common the most important of which is the absence of signs of postcrystalline strain. The only evidence of deformation after crystallization is a small amount of undulose extinction in the larger grains of quartz. There is no sign of movement along boundaries between quartz grains: and the fact that the quartz grains commonly enclose fragments of feldspar and mica suggests that the grain size of the quartz was once small and has since been enlarged by complete recrystallization (see, for comparison, the Ord Ban quartzite: Weiss, McIntyre and Kürsten, 1955, plates IIa and b).

The marbles of the Turoka area are very coarse grained and only a few grains appear in a single thin section. For this reason, and because complete analysis of the fabrics of marbles is time consuming and of little value in a reconnaissance survey, no studies of preferred orientation of calcite have been made. The only minerals studied for preferred orientation are quartz ($[0001]$ -axes in all specimens) and mica ((001) -planes in specimens 530 and 100).

Preferred /

Preferred orientation of quartz and mica: The diagrams showing preferred orientation of quartz and mica are shown in figure 23. Data from each specimen were measured in two mutually perpendicular thin sections (both normal or subnormal to \underline{S}) and rotated into a single plane. In specimens with a lineation this plane is normal or subnormal to the lineation, but in the specimens showing no lineation (378, 102 and 190) the plane of one of the sections was chosen at random. Wherever possible, a total of 300 grains was measured in each specimen; but some of the specimens are so coarse grained that a smaller number of measurements had to suffice. However, in all specimens enough grains were measured to determine the salient features of the pattern of preferred orientation.

With the exception of figure 23d (152), the diagrams for the preferred orientation of $[0001]$ -axes are variations on one basic type. The range of variation in this pattern is expressed by the following sequence of diagrams:

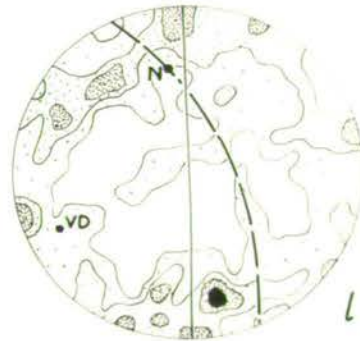
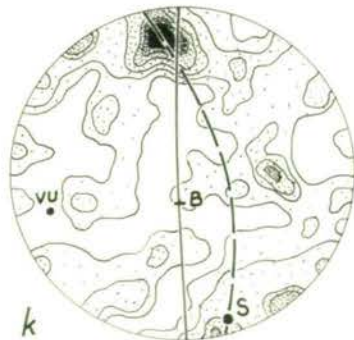
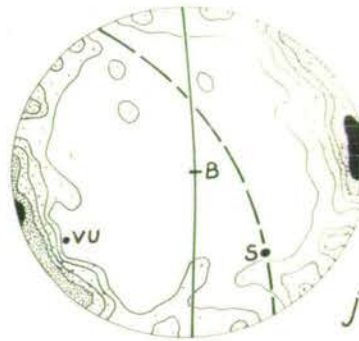
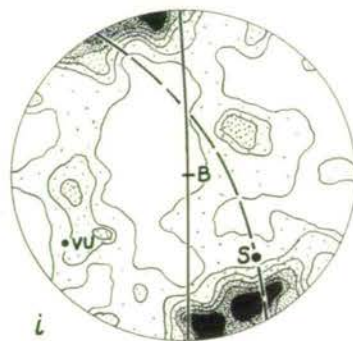
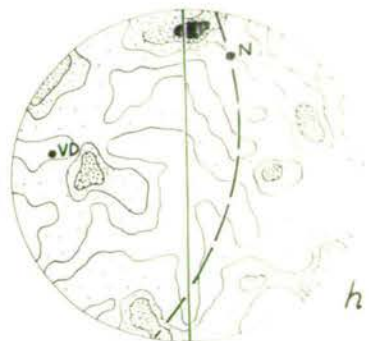
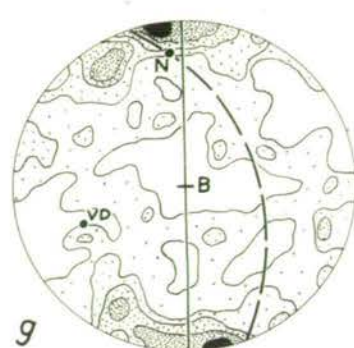
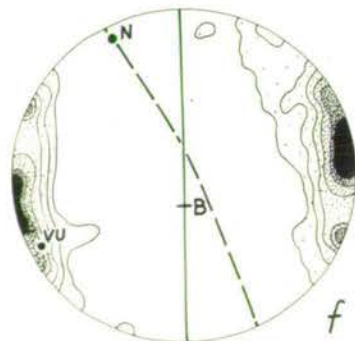
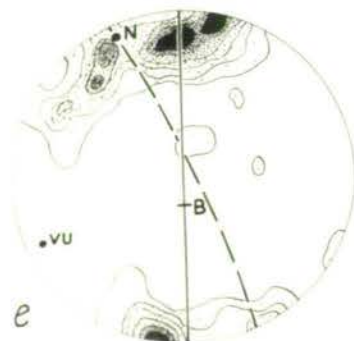
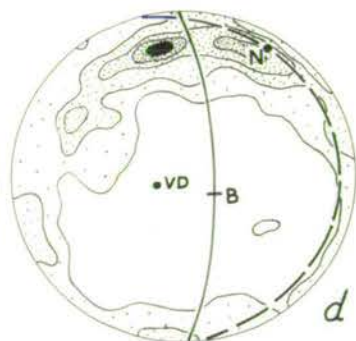
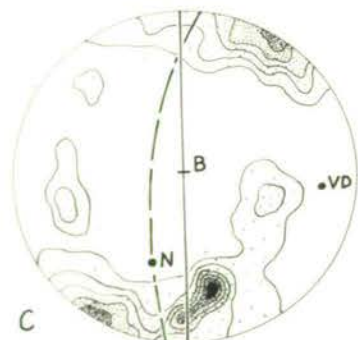
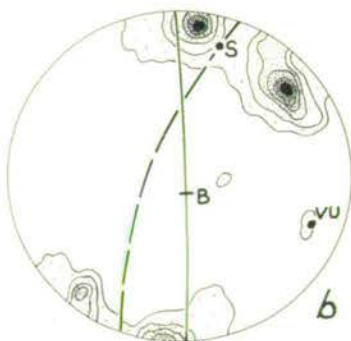
1. Figures 23b (674) and 23e (530); two well-defined closely-spaced maxima symmetrical to the \underline{E} -axis.
2. Figure 23c (128); the maxima are joined by incomplete $(0kl)$ -girdles.
3. Figures 23a (378), 23g (403) and 23l (100); the $(0kl)$ -girdles are complete.

Figure 23. Preferred orientation of quartz and mica in the rocks of Turoka.

- a. Quartzite (378); quartz, 168 [0001] -axes;
contours, 1-3-5-7-9-11% per 1% area.
- b. Quartzite (674); quartz, 300 [0001] -axes;
contours, 1-5-9-13-17-21% per 1% area.
- c. Quartzite (128); quartz, 3300 [0001] -axes;
contours, 1-3-5-7-9-11% per 1% area.
- d. Quartzite (152); quartz, 209 [0001] -axes;
contours, 1-3-5-7-9% per 1% area.
- e. Micaceous quartzite (530); quartz, 250 [0001] -axes;
contours, 1-3-5-7-9-11% per 1% area.
- f. Micaceous quartzite (530); mica, 100 (001)-planes;
contours, 1-3-5-7-9-11% per 1% area.
- g. Granulitic gneiss (403); quartz, 310 [0001] -axes;
contours, 1-2-3-4-5% per 1% area.
- h. Granulitic gneiss (102); quartz, 300 [0001] -axes;
contours, 1-2-3-4% per 1% area.
- i. Granulitic gneiss (100); quartz, 314 [0001] -axes;
contours, 1-2-3-4-5-6% per 1% area.
- j. Granulitic gneiss (100); mica, 104 (001)-planes;
contours, 1-3-5-7-9% per 1% area.
- k. Biotite gneiss (112); quartz, 262 [0001] -axes;
contours, 1-2-3-4-5-6% per 1% area.
- l. Feldspathic gneiss (190); quartz, 300 [0001] -axes;
contours, 1-2-3-4% per 1% area.

V.U. - vertical up; V.D. - vertical down;

S - south; N - north.



4. Figures 23h (102), 23k (112) and 23e (190); the patterns are poorly defined but suggest a general area of high concentration spreading into two (0kl)- or cleft (small circle) girdles.

This sequence is important because it coincides with two other trends in the specimens:

a. From 1 to 4 is a general decrease in importance of lineation.

b. From 1 to 4 is a general decrease in the amount of quartz in each fabric.

It is probable that the patterns represent much the same movement-picture modified locally by changes in intensity of movement and in composition. These two factors may be linked very closely; the amount of penetrative movement in any one fabric may depend upon its composition. The main constituent in the quartzites is, of course, quartz, which is an active structural component. However, in the gneisses, including the more feldspathic granulites, the main constituent is feldspar with interstitial quartz; but feldspar deforms less readily even than interstitial quartz, which thus remains an active component (in contrast to its passive role when interstitial in calcite) and acquires some degree of preferred orientation /

orientation. Quartzite, being more easily deformed than felspathic gneiss, tends to have more penetrative movement concentrated within it; and, in turn, marbles and highly micaceous rocks tend to have more movement concentrated in them than do quartzites.

These views are put forward to explain the variation in detail between patterns of preferred orientation of quartz in a body which appears to have suffered a single uniform deformation. However, although the diagrams show the Tureka area to be inhomogeneous with respect to the degree of preferred orientation of quartz they suggest that it is homogeneous with respect to its symmetry. The difference in the strain of different rocks seems to be one of amount and not one of kind.

The symmetry of most of the diagrams is monoclinic. The patterns show a symmetrical relation to the lineation, confirming this as a E-axis, but the maxima and girdles are not symmetrically arranged with respect to foliation. Figures 23b (674), 23e (530) and 23i (100) show this asymmetry most clearly. Also, the patterns are not of the ac-girdle type indicating translative slip on one set of slip surfaces or more than one set of non-equivalent slip surfaces; they /

they are of a type most frequently associated with orthorhombic symmetry. If the orientation of the foliation is neglected, the symmetry of most of the diagrams is statistically orthorhombic. Examination of individual diagrams in figure 23 suggests that the plane of the horizontal (broken line) has a more symmetrical relation to the patterns of preferred orientation of quartz than does the foliation (full line). This fact is shown most clearly in figures 23b (674), 23c (128), 23e (530) and 23g (403). In order to detect any regional homogeneity in the preferred orientation of quartz (apart from that decided by preferred orientation of lineation), the maxima from all diagrams are plotted on a synoptic diagram for the whole area. This diagram is shown viewed along the plunge of the regional E-axis, as defined by macroscopic and megascopic structures, in figure 24. The black circles are maxima of 5% per 1% area and over, and the open circles are maxima of between 3% and 5% per 1% area. The pattern which emerges in this diagram indicates a striking degree of regional homogeneity with respect to the preferred orientation of quartz. This pattern is symmetrically oriented with reference to the intersection of the plane of projection and the horizontal and with reference to /

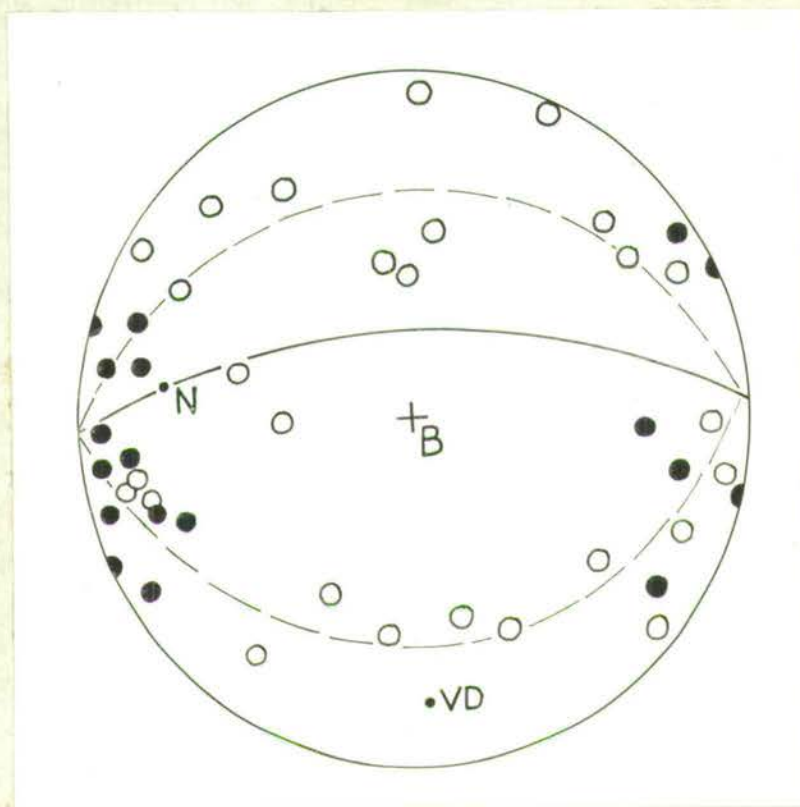


Figure 24. Synoptic diagram of $[0001]$ -axes of quartz; black circles, maxima of 5% per 1% area and over; open circles, maxima of between 3% and 5% per 1% area.

V.D. - vertical down; N - north.

to the regional \underline{E} -axis. It appears to be similar in form to the patterns from individual specimens, namely, an area of high concentration spreading into two ($\underline{Ok1}$)-girdles. The symmetry of this diagram is statistically orthorhombic and agrees with the symmetry of the $\underline{\Pi}$ -diagram (figure 20b). But fabrics on a macroscopic scale have monoclinic symmetry because \underline{S} is folded; and individual fields on a microscopic scale also have monoclinic symmetry because \underline{S} is oriented asymmetrically with respect to the planes of symmetry of the orthorhombic patterns of quartz. There is no doubt that in all the analysed specimens quartz is an active structural component. Mica, on the other hand is, in the view of the writer, a passive component. It occurs in isolated flakes either in quartz (in the quartzites) or in quartz and feldspar (in the gneisses). Likewise, on a larger scale, the foliation in some of the quartzites and felspathic granulites and gneisses is a passive structural element. It is defined only by weak compositional layering and appears to have no mechanical significance. Only in the micaceous gneisses does it appear to be a surface of slip in the last stages of deformation and in these it becomes alternately passive and active by transposition, as outlined above. The tectonite from /

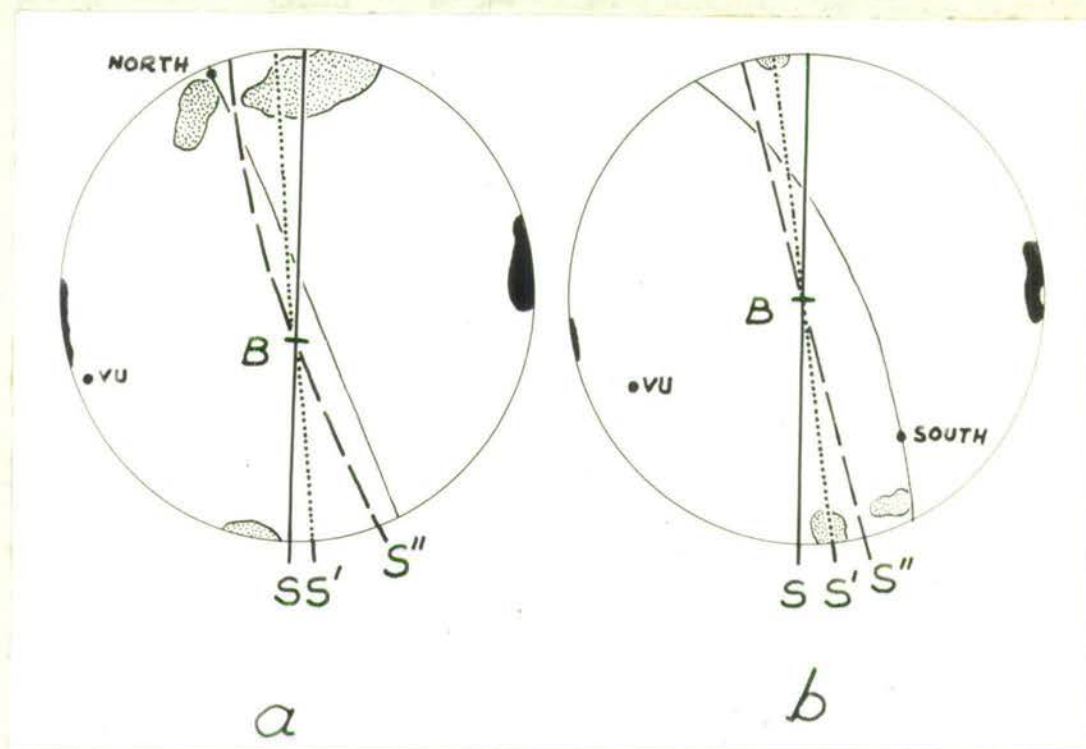


Figure 25. Orientation data for specimens 530 (a) and 100 (b). Explanation in text. V.U. - vertical up.

from Anglesey described by the writer (Weiss, 1955) shows how the symmetry of a passive structural component, if it is different from the symmetry of active structural components, can change the symmetry of a fabric until it no longer agrees with symmetry of strain. In the rocks of Turoka, on a macroscopic scale, it is only where S is folded that the symmetry is monoclinic. In the analysed specimens too, it is the passive structural elements that define monoclinic symmetry for the whole fabric. This is demonstrated by figures 25a (530) and 25b (100); the three planes S, S' and S'' are respectively the foliation, the plane defined by the preferred orientation of mica-flakes (from figures 23f and 23j) and one of the planes of symmetry of the pattern of preferred orientation of quartz (from figures 23e and 23i). The three surfaces intersect in B and the overall symmetry of the fabrics is monoclinic. If the symmetry of the passive components (S and S') is neglected, the symmetry defined by the preferred orientation of quartz is orthorhombic.

5. Kinematic interpretation of structural data

The regional foliation of the Turoka area cannot be unrolled and levelled in the same fashion as a sedimentary S because /

because the foliation of the gneisses is, at least in part, mechanical in origin. However, it is probable that the bounding surfaces of the larger bodies of marble correspond, in a broad fashion, to original sedimentary surfaces; and, if it is assumed that these layers of marble once were planar and horizontal, then the following general conclusions can be drawn from their present forms as expressed in the profile:

1. A phase of intense unrestricted transport early in the kinematic history of the structures must be invoked in order to explain the rootless condition of the large folds of marble, the existence of large tectonic inclusions of one rock type in another and the lensoid form of the lithological units on all scales.

2. The cylindroidal folding of the marbles implies a shortening or a monoclinic transport or both in a direction normal to the fold axis (E).

3. The deformation did not consist only of a simple horizontally directed squeezing or shearing, because the axial surfaces of the larger folds are inclined at a low angle to the horizontal, and the fold axes plunge.

If the plunge of the regional fold axis is neglected, the synoptic diagrams for S, E and the preferred orientation of quartz collectively define orthorhombic symmetry for the whole /

whole area. Because of the plunge of \underline{B} the three planes of symmetry of the orthorhombic synoptic diagrams have only a partially symmetrical relation to the horizontal: two of them (one containing \underline{B} and one normal to \underline{B}) intersect in a horizontal line, the remaining plane is vertical (respectively \underline{P}_1 , \underline{P}_2 and \underline{P}_3 in figure 26). Before proceeding to a kinematic interpretation of these and other structural data, it is necessary to make several assumptions regarding the orientation of axes of principal stress in the crust of the earth on an orogenic scale, as follows:

1. Where external stress is non-rotational, one axis of principle stress is vertical and two are horizontal (see Anderson, 1951, p. 12).

2. Where external stress is rotational (a force-couple) the plane of the force-couple is either vertical or horizontal.

If these assumptions are made, then it is apparent that the structures produced by unbalanced orogenic stresses in the crust of the earth must bear, on an orogenic scale, some geometrical relation to the horizontal. Because of the effects of structural anisotropy present in a rock before deformation, strain does not always correspond in symmetry with external stress, so that axes of principal strain cannot be always equated, on all scales, with axes of principal stress; it has already /

already been shown how a simple horizontal biaxial strain with orthorhombic symmetry can produce monoclinic movements (flexural slip folding of a layered body) on a small scale. But if a field is large enough for strain in it to be considered statistically homogeneous (even if deformation is by flexural slip folding), then axes of principal strain can be equated in a general fashion with axes of principal stress. This is true not only of non-rotational stress but also of rotational stress (a force-couple) which can be resolved into three mutually perpendicular axes of principal stress in the same way as non-rotational stress; but, where stress is rotational, two of the axes of principal stress rotate about the third axis (the normal to the plane of the force-couple) so that, on an orogenic scale, a force-couple acting in a vertical plane produces a consistent asymmetry in the orientation of structural elements with reference to the horizontal. The effects of rotation are difficult to detect where the force-couple acts in a horizontal plane because rotation is about a vertical axis and no asymmetry is produced with reference to the horizontal.

The synoptic diagrams for the Turoka area suggests that the strain of the area as a whole may be considered statistically /

statistically homogeneous because the monoclinic symmetry of fabric caused by the presence of flexural slip folds is statistically insignificant on the scale of the whole area. But the orthorhombic synoptic patterns depicting statistically homogeneous strain are asymmetrically oriented with reference to the horizontal (E plunges). Overall rotational strain thus is present. It is obvious that there is an axis of rotation inclined to E because E itself is rotated into a plunging position; but the plunge of E alone is no guide to the orientation of this axis because an axis can acquire a plunge by rotation about any other axis which is not vertical. From the orientation of the three planes of symmetry of the synoptic diagrams it can be seen also that E is not an axis of rotation, in the last movements, on the scale of the whole area. If it were it would have rotated the horizontal axis of intersection of two of the planes of symmetry into a plunging orientation. The only single axis of rotation which can explain both the plunge of E and the horizontal orientation of the axis of intersection of the planes of symmetry is the axis of intersection itself (E' in figure 26). The rotation of the whole field about E' could have occurred either before or after the formation of E. For each of these cases there /

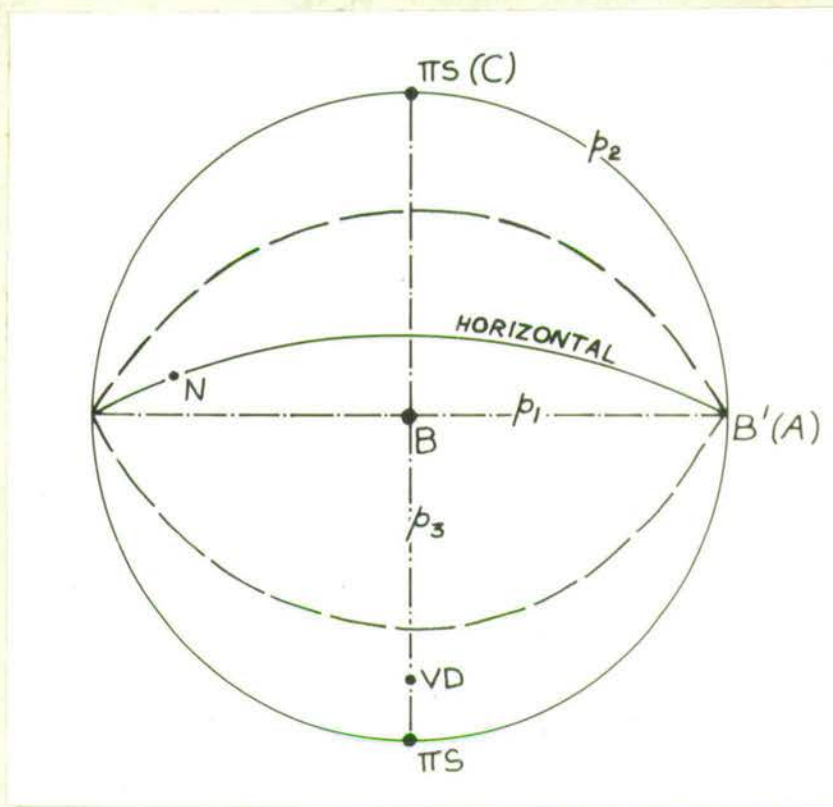


Figure 26. Synoptic diagram for all penetrative structures (explanation in text)

there are two possible alternative kinematic interpretations. The fold axis could have formed initially with a plunging orientation on a dipping \underline{S} in one of two ways:

1. \underline{E} could have been produced by a triaxial strain in which the axis of greatest shortening was initially normal to \underline{E}' but became normal to \underline{E} in the later stages of deformation. This deformation corresponds to that outlined above for parts of the Scottish Highlands on the basis of Anderson's observations ($\underline{E} \perp \underline{E}'$ -tectonics). The later movements normal to \underline{E} were more intense and penetrative than the earlier movements normal to \underline{E}' .

2. \underline{E} could have been produced by biaxial strain of rocks in which \underline{S} already had a regular easterly dip produced by earlier unrelated movements ($\underline{E} \wedge \underline{E}'$ -tectonics).

If \underline{E} was formed initially in horizontal \underline{S} , then it acquired its present plunge in one of two ways:

1. \underline{E} was tilted in the last stages of or after its formation in response to the appearance of an element of triaxial strain in a deformation previously biaxial ($\underline{E} \perp \underline{E}'$ -tectonics).

2. \underline{E} was tilted after formation by later genetically unrelated movements ($\underline{E} \wedge \underline{E}'$ -tectonics).

On the basis of Sander's empirical argument (1948, p. 180) /

p. 180) it is possible to eliminate the second of each of these pairs of alternatives, because, from the synoptic diagram, \underline{B} is statistically normal to \underline{B}' ; and it can be assumed that the two axes are genetically connected. There remains the problem of the chronology of movements about \underline{B} and \underline{B}' ; but before considering this it is necessary to determine the nature of the strains and stresses which produced the penetrative structures associated with \underline{B} .

In the symmetry of the synoptic diagrams is preserved the symmetry of the last stage of what may be a long line of kinematic evolution. The three axes of principal strain of this stage are the intersections of the three planes of symmetry one of which is \underline{B} and another \underline{B}' . The presence of flexural slip folds proves that at one stage of kinematic evolution deformation was by slip on \underline{S} . If the strain in this stage is biaxial, then \underline{B} , as the fold axis, is an axis of no change, and one of the remaining axes of principal strain is an axis of extension and the other an axis of compression. On a small scale, a fabric produced by this strain has monoclinic symmetry, and, on a large scale, orthorhombic symmetry (deformation is statistically homogeneous on a large scale). /

scale). If strain is triaxial, \underline{E} , also, is either an axis of compression or extension. It has already been shown that triaxial strain by slip on \underline{S} , where \underline{E} is an axis of shortening, ideally produces $\underline{E} \perp \underline{E}'$ -structures with triclinic symmetry on all scales. Although movements of this kind could account for the plunge of \underline{E} , as outlined above, the triaxial element of strain must have been present before or after the phase of movement which produced \underline{E} because the symmetry of the penetrative structures is monoclinic and not triclinic on a small scale. There is, however, another kind of triaxial strain where \underline{E} is an axis of extension. This strain cannot be achieved by slip on \underline{S} alone. It belongs properly to a late stage in a line of kinematic evolution where \underline{S} is passive and other flow surfaces appear in a fabric. But an initially biaxial strain by slip on foliation can pass into a triaxial strain of this kind, with no change in the pattern of deforming stresses, giving rise to fabrics which have, according to scale of investigation, either monoclinic or orthorhombic symmetry. Such a deformation has been termed axial flow by the writer (Weiss, 1954, pp. 76-78) because it results in extension along an already formed fold axis. The penetrative structures of the Turoka area could have been produced by this kind of deformation because /

deformation because their symmetry is of the right kind; but this kind of triaxial strain cannot in itself account for the plunge of E, and structural evidence of extension along E is slight. It is simpler to view the folding about E as a product of biaxial strain by slip on foliation. The symmetry of this deformation can be statistically the same as that of axial flow. If the strain that formed the penetrative structures is assumed to be biaxial, then what remains to be considered is the identity of the mutually perpendicular axes of principal strain normal to E. If the axis of extension is labelled A and the axis of compression is labelled C, then there are two possibilities:

1. A is normal to E in a vertical plane and C is horizontal (E' coincides with C).
2. C is normal to E in a vertical plane and A is horizontal (E' coincides with A).

The symmetry of both of these strains agrees with the symmetry of the synoptic diagrams. Because the strain is statistically homogeneous, it is possible to equate axes of principal strain with axes of principal stress whether the external stress is rotational or non-rotational. A is parallel to the axis of least principal stress, E to the axis of intermediate /

intermediate principal stress and C to the axis of greatest principal stress (direction of compression - P). Thus, in the Turoka area, there are two possible dynamic patterns which could have produced the penetrative structures, as follows:

1. P is horizontal and normal to E .
2. P is normal to E in a vertical plane.

At first sight, the first possibility is most attractive; but examination of the folds, both in the field and in the profile, shows that although on a large scale they have the symmetry required by this orientation of P , they do not have the necessary geometry on any scale. Folds produced by a horizontal P have vertical axial planes, not shallowly dipping axial planes like the folds of Turoka. Likewise, the geometry of the preferred orientation of quartz does not support the first interpretation: the presence of $(Ok1)$ -girdles probably indicates an element of "flattening" in a direction symmetrically intersecting the angle made by the planes of the girdles (see, for instance, Turner, 1948, pp. 222-223). At Turoka, a horizontal P would coincide with the axis of intersection of these planes.

The second possibility is more promising. The axial planes of the folds are normal to P and so is the bisector of one /

one of the angles between the (Okl)-girdles in the quartz patterns. But two difficulties arise:

1. It was assumed above that axes of principal stress in the crust of the earth, where stress is non-rotational, are either vertical or horizontal. In the Turoka area, the symmetry of the synoptic diagrams shows that the stresses which completed the kinematic evolution of the penetrative structures were non-rotational about E, and yet P is inclined. The axis of rotation responsible for this inclination is E' and it must be concluded that the rotation about E' which caused E to plunge occurred as an impenetrative movement after the formation of E by the action of P. Although the E \perp E'-relation of the two tectonic axes suggests that they are genetically related (according to Sander) and a product of overall triaxial strain, the above features of the penetrative structures favours the appearance of triaxial strain late in the kinematic history of the rock body after a phase of intense biaxial strain which produced the penetrative structures. This interpretation corresponds to the second of the two possible E \perp E'-relations listed above. The plunge of E, in this instance, is probably analogous to the plunge, between depressions and culminations, of the E-axis of the Swiss Alps.

2. It is difficult to envisage the formation of folds where \underline{P} initially is normal to the surfaces which become folded. From features of the profile it already has been concluded that an early phase of unrestricted (monoclinic) transport must be invoked to explain the form of the folds. It is further suggested that all flexural slip folds of \underline{S} were initiated in this early phase of movement during which \underline{P} had a different orientation. A possible evolutionary sequence for the penetrative structures of the Turoka area is as follows:

a. Horizontal squeezing of horizontal layers produces flexural slip folds with vertical axial surfaces. Overall symmetry is orthorhombic (figure 27a).

b. External stress becomes rotational owing to the action of a force-couple (\underline{E}_1 and \underline{E}_2) and \underline{P} rotates in a vertical plane. There is a transition from horizontal squeezing to horizontal shearing as the orogeny enters the phase of greatest strain. The axial planes of the folds become uniformly inclined and symmetry of the whole field becomes monoclinic (figure 27b). On grounds of symmetry alone it is impossible to deduce a sense for this rotation on the Turoka area. If the view that the Turoka fold rooted in the south is correct, then the sense could be anticlockwise as viewed down the plunge of \underline{E} .

c. /

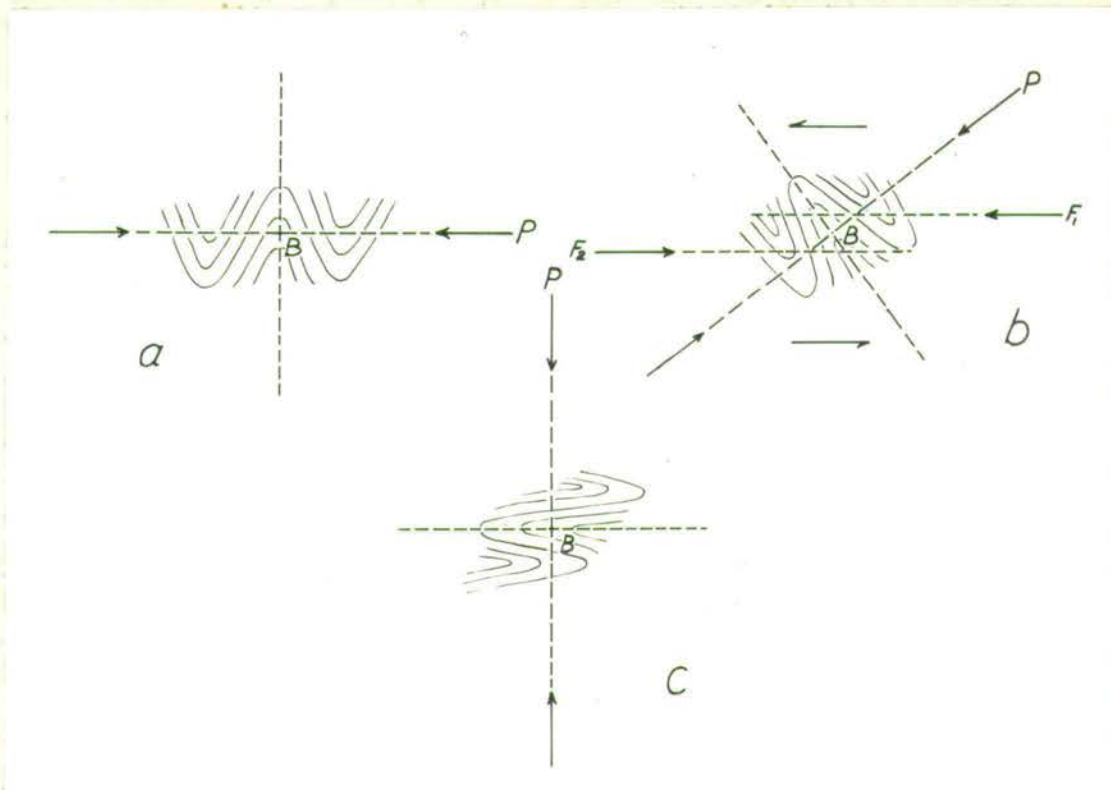


Figure 27. Development of folds in the Turoka area (diagrammatical).

c. Inclination of \underline{P} increases until tangential shearing passes into flattening or vertical loading, as a result of deep burial under a great orogenic thickening, and \underline{P} becomes vertical. Transport is once again restricted and the symmetry of deformation and fabric becomes orthorhombic: but the geometry of the fabric is different from the geometry of phase a, above, because the axial surfaces of the folds are rotated into a horizontal orientation (figure 27c). It is at this stage that the mechanism of flow changes finally in the non-micaceous rocks so that flow is independent of \underline{S} as a slip surface and strain is homogeneous even on a microscopic scale. This is shown by the development of a homogeneous preferred orientation of quartz independent of \underline{S} on the microscopic scale. The foliation has been neutralized as a surface of slip, by folding. Only in the micaceous rocks does \underline{S} remain a surface of slip: in these rocks, on account of the properties of mica, \underline{S} can become transposed by folding into a new foliation and does not become structurally passive. In the quartzose rocks the flakes of mica become passive like the foliation. Figures 25a and 25b suggest that the mica flakes in the last stage of deformation are in process of passively rotating from \underline{S} towards the "plaiting surface" (surface of flattening normal to \underline{B}) defined by the homogeneous preferred /

preferred orientation of quartz.

After the formation of these penetrative structures, a slight flexing about $\underline{B'}$ produced the observed plunge of \underline{B} .

THE
ROYAL EDWARD
SPECIAL

V. GENERAL SUMMARY AND CONCLUSIONS

Statistical analysis shows that the Turoka area is homogeneous with respect to a E-axis of cylindroidal folding plunging at 20° in direction north 62° east. This is the only statistically recognizable fold axis in the area. There is no sign in the Turoka area of the horizontal fold axis trending north-north-west proposed by Joubert to account for stratigraphic repetition of beds in the Namanga-Bissel area. The folds observed about the easterly plunging axes are recumbent on all scales, so that repetition of stratigraphical horizons with constant strike and dip can equally well be a result of folding about this axis. The apparently anomalous steeply dipping layers that strike normal to the regional strike (the initial problem in the investigation) are not anomalous, they are layers near the hinges of large folds. They have this strike because, where folding is cylindroidal, all vertical attitudes of the folded surfaces strike parallel to the trend of the fold axis, and, where recumbent folds have plunging axes, this trend is normal to the regional strike.

The most important general conclusion which can be drawn from the geometrical analysis concerns the dangers attached /

attached to the assumption of an orogenic axial trend parallel to a regional strike. Commonly this assumption can be justifiably made, especially where axial surfaces of folds are steep or fold axes are horizontal. But, where folds are recumbent or fold axes plunge, the regional strike can depart widely from parallelism with axial trend. Such structures are particularly confusing in areas of low relief and poor exposure as in Kenya.

In the view of the writer the sequence of tectonic events in the Turoka area may be summarized as follows:

1. Intense monoclinic strain of a layered body produces flexural slip folding on all scales about a regionally constant fold axis. Shearing and unrestricted transport tear apart initial sedimentary layers of marble into isolated tectonic inclusions of various sizes. One layer, in the north of the area, is rolled up into a cylinder about a core of granulitic gneiss. In this phase, deformation is inhomogeneous on a small scale, although it may be statistically homogeneous on the scale of the whole field. As deformation proceeds, \underline{S} in the micaceous gneisses is transposed by folding into a new \underline{S} , whereas in the non-micaceous rocks the initial layering is "neutralized" by folding and becomes structurally passive. Strain tends to become statistically homogeneous on /

on smaller and smaller scales.

2. Change in the pattern of stresses, probably caused by deepening burial under an ever-growing orogenic pile, changes the symmetry of strain from monoclinic (unrestricted transport) to orthorhombic (restricted transport), and P rotates in a vertical plane. Its initial orientation may have been either horizontal (tangential squeezing) or inclined (tangential shearing), but it rotates towards the vertical (vertical squeezing). The axial surfaces of the folds are progressively rotated in a constant sense from their initial orientation (vertical or inclined) to a horizontal orientation. Deformation becomes statistically homogeneous on all scales and active components (quartz) in the microfabric acquire a homogeneous preferred orientation with orthorhombic symmetry.

3. After the completion of these penetrative movements, the whole field is externally rotated about a horizontal axis (B'), normal to B, to give the observed plunge. There is no penetrative imprint of this movement in the microfabric and it must have taken place in a non-tectonic environment. The fact that this axis is normal to B suggests that it is genetically related, representing, perhaps, a late-stage element of triaxial strain.

In /

In the Turoka area, the main tectonic axis (the orogenic trend) is the plunging E-axis. On an orogenic scale, the axis of greatest principle stress (P) lay in the plane normal to the axis, although it occupied successive positions, as outlined above. This picture of stresses contrasts sharply with that necessary for Joubert's kinematic interpretation which requires the axis of greatest principal stress to have a low inclination in a vertical plane striking east-north-east. The question raised by the new interpretation is, over how great an area of the Basement System of southern Kenya can this interpretation be extended? Some clue to the answer is obtained from figure 28 which shows Π -poles and lineations measured outside the Turoka area. The position of the Π -girdle and the E-maximum from Turoka are shown on each diagram for comparison. Figure 28a is from a small hill of gneiss at Lormoto in the centre of the Namanga-Bissel area about 40 miles south of Turoka. The geometry and symmetry of the structures is the same as in the Turoka area. However, in the extreme south of the Namanga-Bissel area on the southern spur of Ol Doinyo Orok, granulitic gneisses have a lineation the trend of which has swung through some 40° to the south-east with reference to the lineation in Turoka. In another direction, figure /

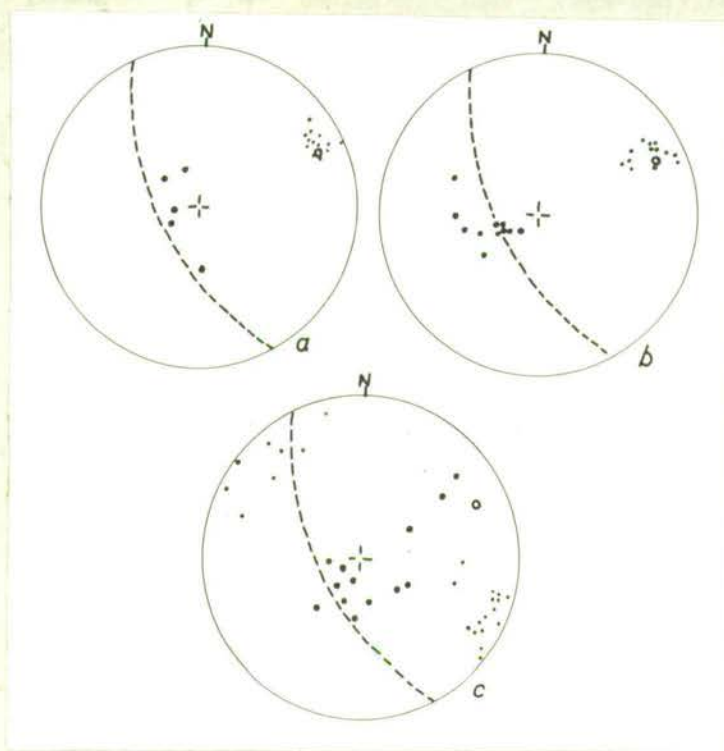


Figure 28. Partial diagrams for areas outside the Turoka area (megascopic scale); large dots, Π -poles; small dots, lineations and small folds.

figure 28b shows the orientation of penetrative structures from the area to the west of Kiu, about 20 miles east of Turoka. Again, the structures have the same orientation as those of Turoka. Further to the east, however, near Opete in the east of the southern Machakos quadrangle mapped by Baker, Π -poles, lineation and small folds show a different pattern (figure 28c). The regional E -axis in that area appears to plunge gently to the east-south-east. But the structures are far less regular than in the Turoka area, and figure 28c has been prepared without proper regard for local variations in homogeneity.

The structural picture found in the Turoka area probably is widespread in the surrounding rocks. From figures 28a and 28b the area homogeneous with respect to E can be very roughly extended over an area of many hundreds of square miles compared with the 40 square miles of the Turoka area. The actual extent of the area of homogeneity and its structural relation to adjoining areas with different geometry is a problem which must remain with the geologists of the Survey. The writer believes that, using the correct methods of geometrical analysis, this problem could be solved by geologists in the course of reconnaissance survey. It is hoped that the general principles outlined in this paper help to show how this can be done.



Plate 1. Regular foliation and lineation in
biotite gneiss.



Plate 2. Folds in impure marble.



Plate 3. Folds of feldspathic gneiss in
 biotite gneiss.



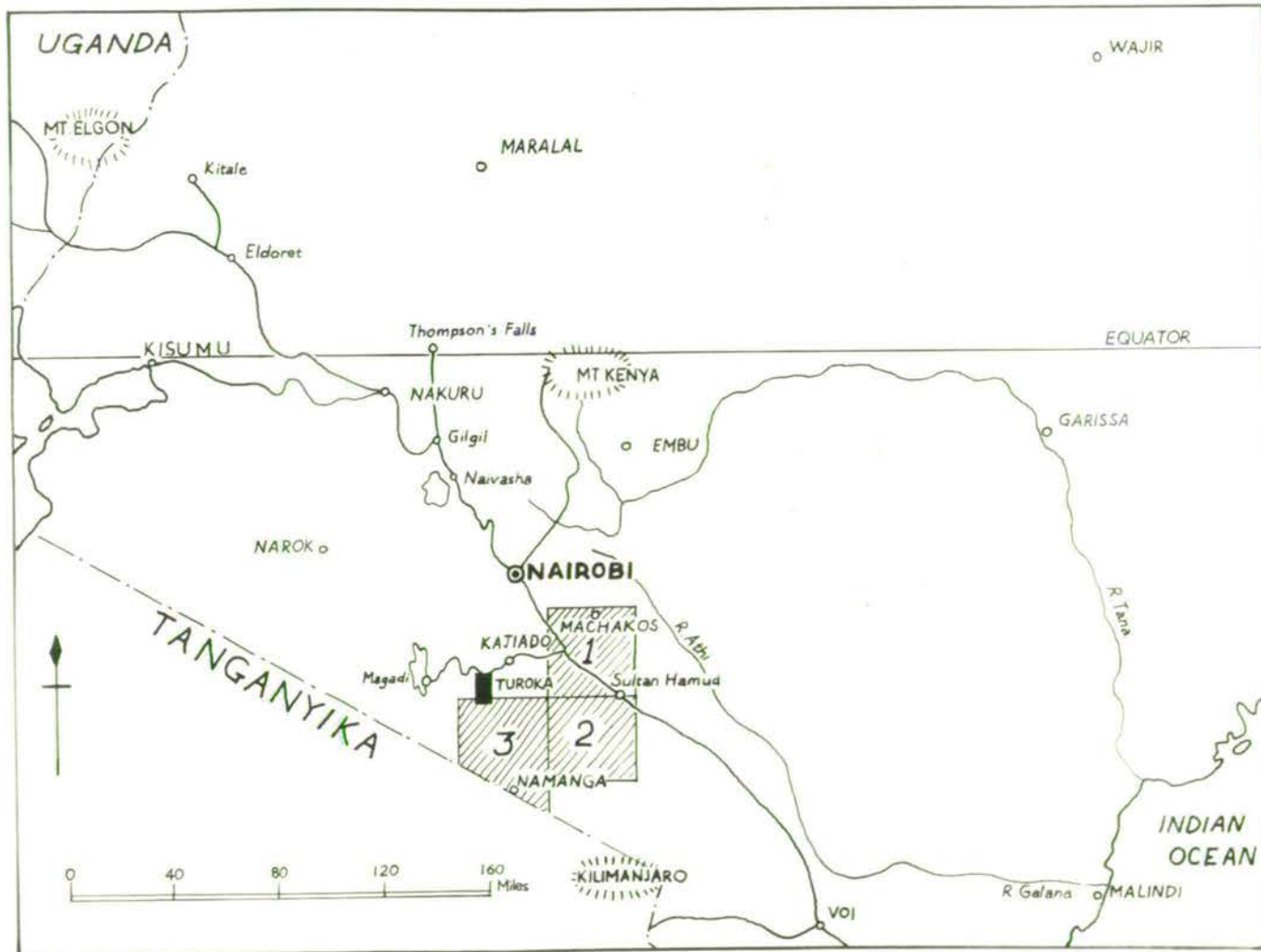
Plate 4. Lineation in feldspathic biotite gneiss.



Plate 5. Oblique joints and lineation in feldspathic gneiss.














Plate 6. ac-joints and lineation in hornblende gneiss.



KEY TO SYMBOLS USED IN MAPS AND PROFILES

IN MAP 2 AND MAP 3





	UNDIFFERENTIATED GNEISS.		TREND & PLUNGE OF FOLD AXIS & LINEATION.
	GNEISS OF CORE.		STRIKE & DIP OF FOLIATION.
	QUARTZITE.		GENERALIZED TRACES OF FORM SURFACES.
	MARBLE.		RAILWAY.
	KAPITI PHONOLITE.		TRACK.
			RIVER.

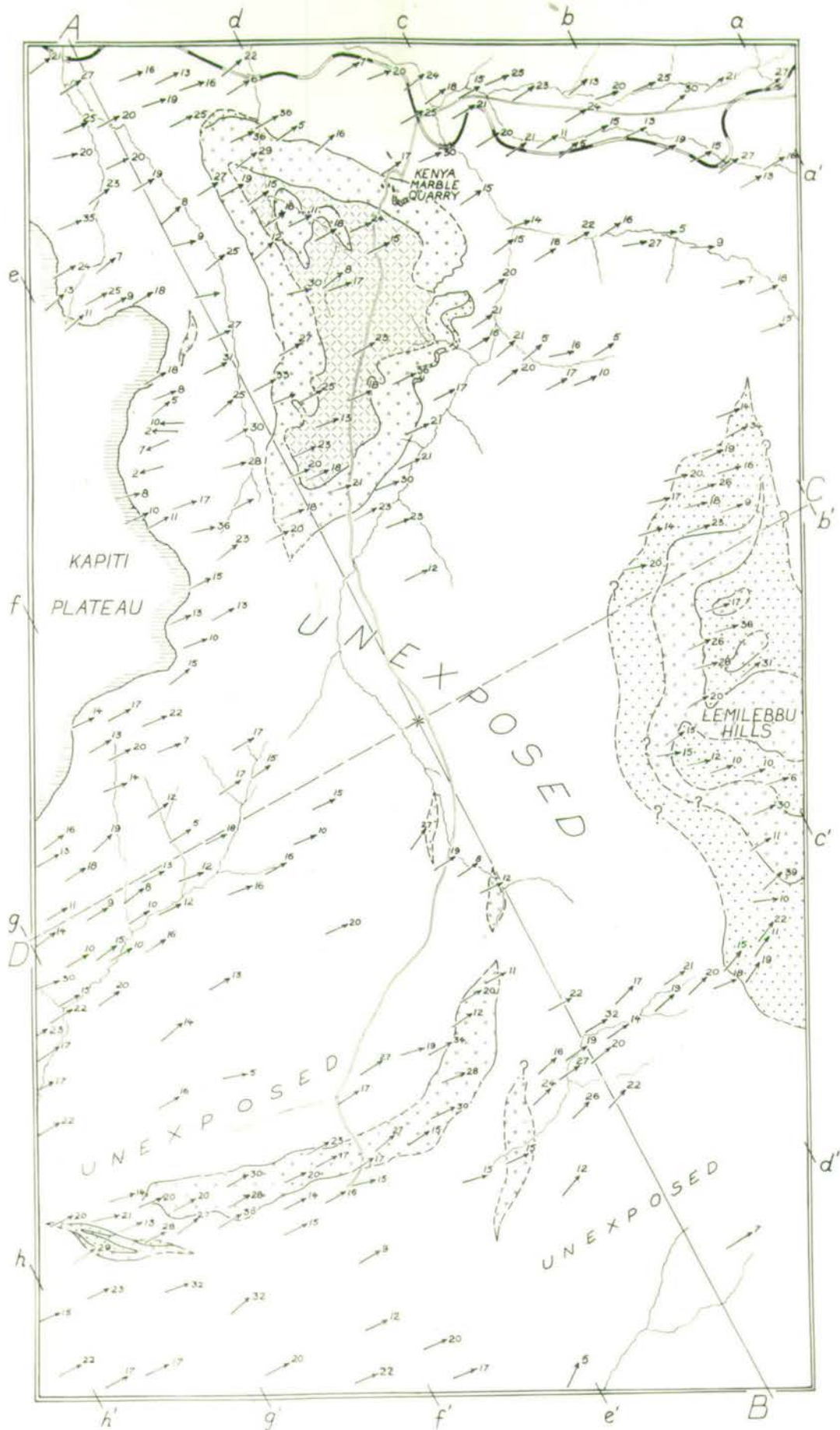
·6735' APPROXIMATE SPOT HEIGHTS IN FEET
(ANEROID)

IN PROFILE 1

	GNEISS.
	QUARTZITE.
	MARBLE.

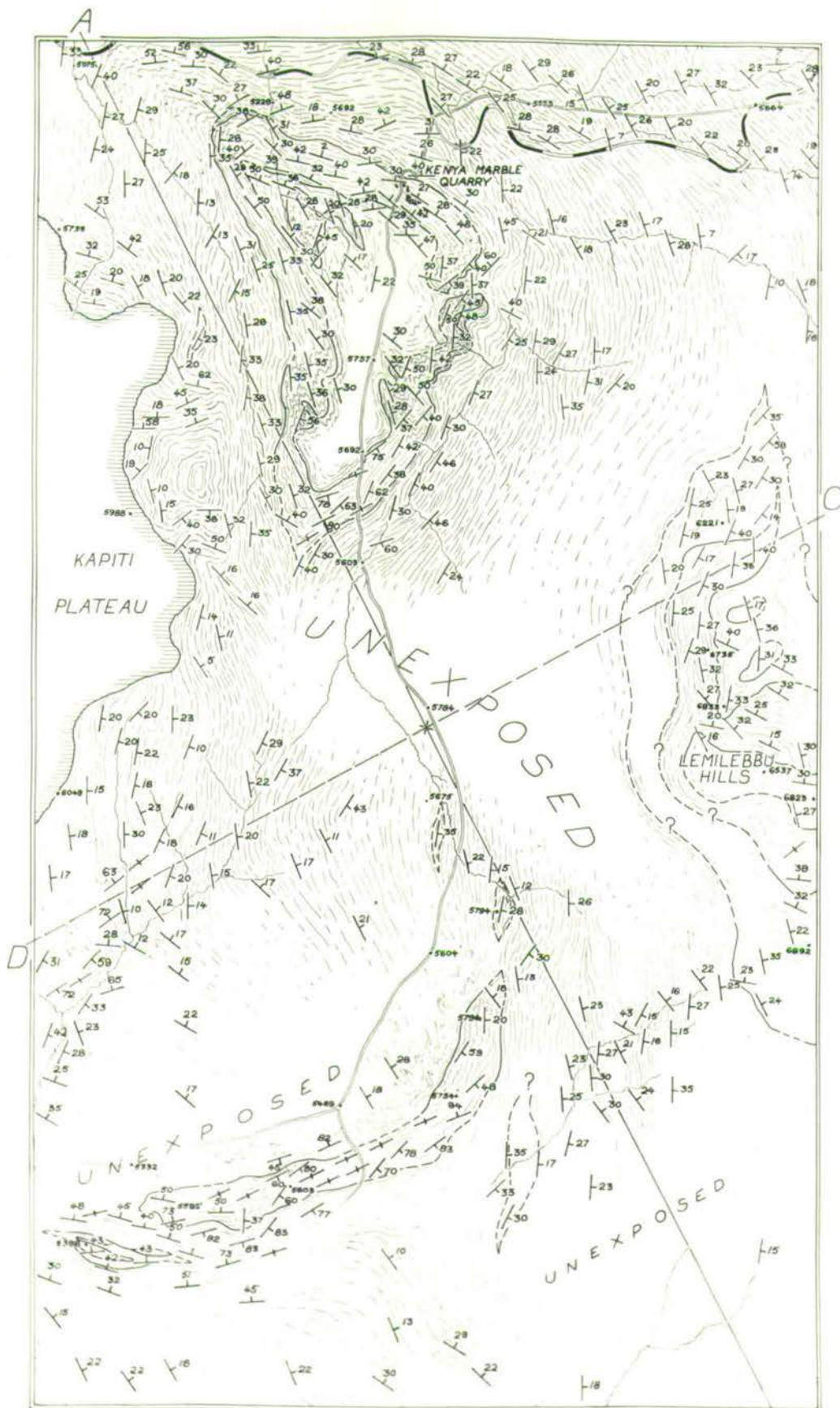
IN PROFILE 2

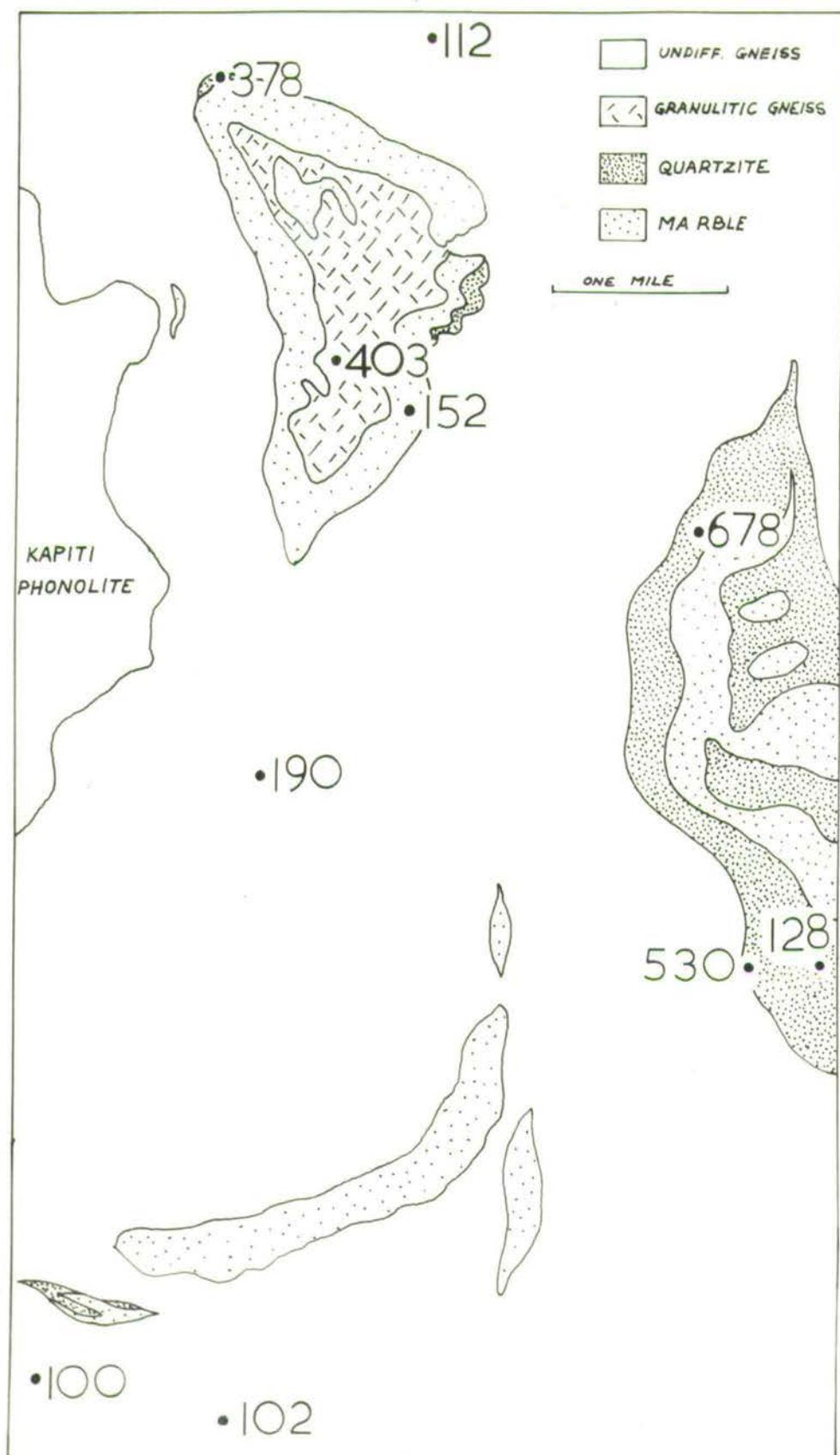
	GNEISS.
	QUARTZITE.
	MARBLE.
	KAPITI PHONOLITE.



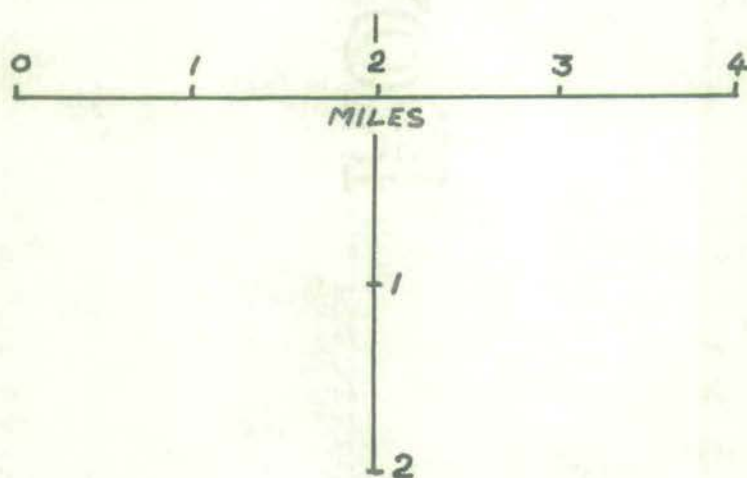
Map 3. Structural map showing orientation of foliation.

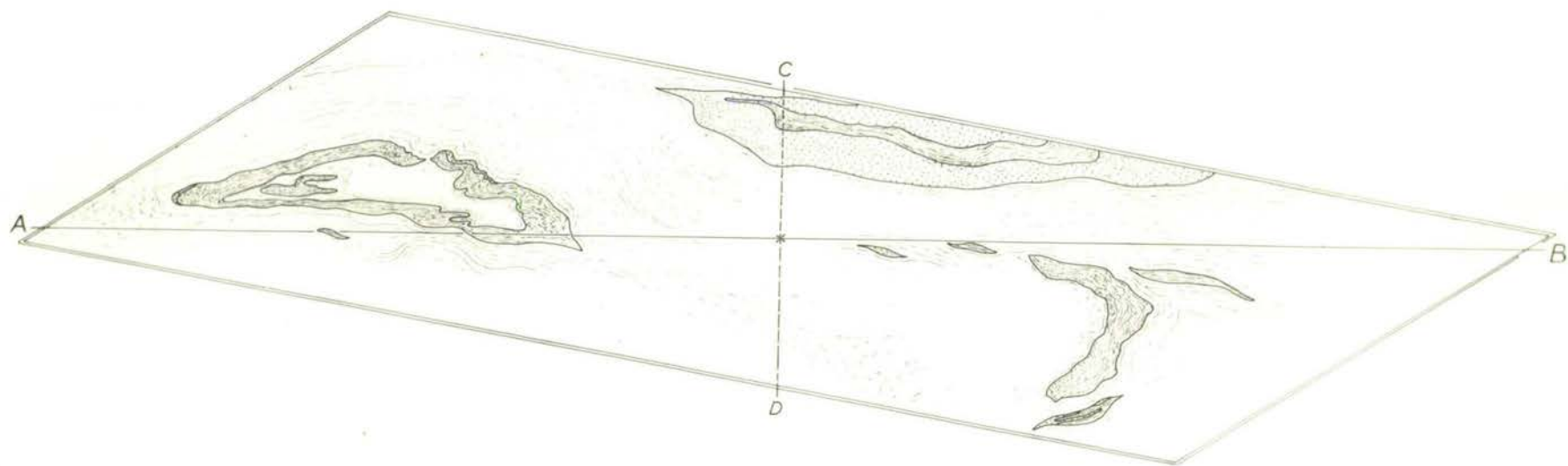




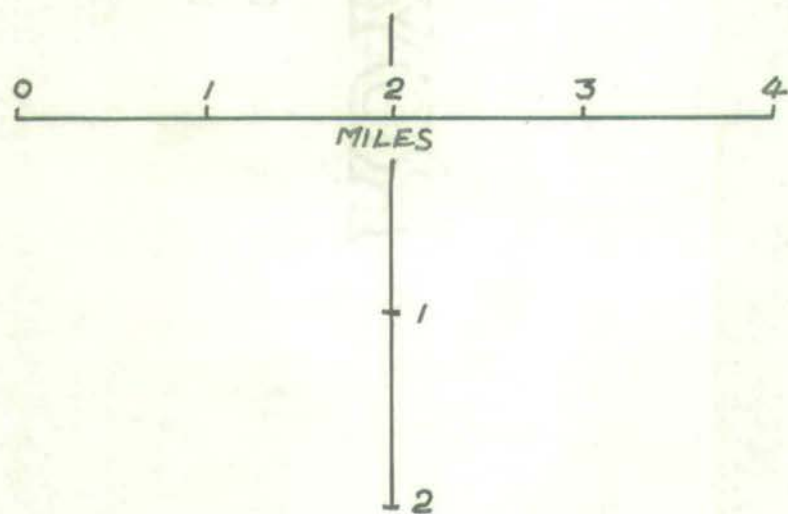


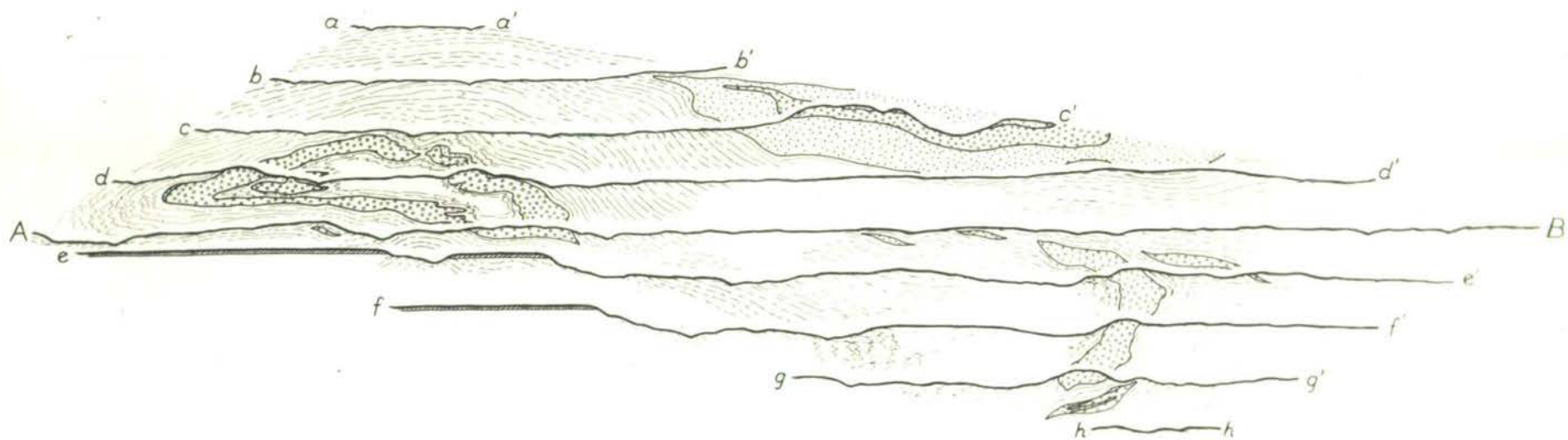
Profile 1. Transverse profile; plane of projection
strikes north 28° west and dips 70° west.





Profile 2. Coulisse profiles; position of each topographic profile is shown on map 2.





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II. 9. Structural Analysis at Loch Leven,
Argyllshire.

STRUCTURAL ANALYSIS AT LOCH LEVEN, ARGYLL

- A PRELIMINARY SUMMARY

by L. E. WEISS

I. INTRODUCTION

II. PENETRATIVE STRUCTURES

General statement
Structural surfaces
Structural axes

III. STATISTICAL ANALYSIS

General statement
S
B and B'
S X S' and S'

IV. CONCLUSIONS

V. REFERENCES

I. INTRODUCTION

The formation of deformed rocks surrounding the upper part of Loch Leven in Argyllshire and Inverness-shire presents an interesting study of differential deformation in rocks of contrasted mechanical properties. For many years now, it has been recognized that current bedding and other phenomena of sedimentary origin are well preserved in the great bodies of light-coloured quartzite which occur in the formation, and these structures have been used, especially by Bailey (see, for instance, 1930, 1934) in determining upper and lower surfaces of individual layers of quartzite, and, beyond this, in erecting stratigraphical successions. Most of the quartzites have suffered so little internal reconstruction in response to deformation that they hardly fall into the category of tectonites. However, the layers of mica schist, some of them very thick, which separate the individual bodies of quartzite, are intensely strained and internally reconstructed. The survival of sedimentary structures in the quartzitic members of otherwise strongly deformed bodies of rock is not universally found, even in the Highlands, and such a survival suggests special conditions of deformation. One of the special conditions in the Loch Leven area is the presence /

presence of the strongly laminated structurally incompetent micaceous rocks in which the quartzites "float". The strain which, during deformation, would have been disseminated uniformly throughout a compositionally homogeneous body of rock has been, in the Loch Leven area, differentially disseminated in the quartzites and the mica schists so that most of the penetrative movement has been concentrated in the kinematically susceptible mica schist. This fact can be established readily by contrasting the structural features of the two rock types in almost any roadside exposure near the shores of Loch Leven.

The deformation which has affected the quartzites and mica schists has produced in these rocks penetrative structures of various kinds. The movements concentrated in the schists have formed folds, lineations, slip surfaces and so on, with great profusion and perplexing complexity. It is the purpose of this summary to describe briefly the geometrical features of some of these penetrative structures and the interpretation placed upon them. The "stratigraphy" of the rocks is beyond the scope of this summary; enough has already been written on the subject by previous workers. The structural synthesis made by Bailey is an example of a determination of structure by pure stratigraphy. On the basis of sedimentary structures (such /

(such as current bedding) and lithological resemblances between individual bodies of quartzite or schist, Bailey has erected^a stratigraphical column for the formation. Departures from this ideal stratigraphical sequence, shown by the rocks in certain parts of the area, have then been used to establish the presence of folds and slides (for example, Bailey, 1934, pp. 500-501). In the view of the writer, such a procedure is philosophically unsound as an approach to the study of structures in deformed rocks (Weiss, 1956). But, whether or not Bailey's synthesis is valid, the fact remains that no satisfactory studies of structural geometry in three dimensions have yet been made in this part of the Highlands.

This summary presents the preliminary results of a much more extensive study, as yet uncompleted. The area discussed here is the part of upper Loch Leven extending on the south side of the Loch, from Invercoe to Kinlochleven, including Sgor na Ciche and Garbh Bheinn, and, on the north side of the Loch, from Callert to Kinlochleven, south of a line joining the summits of Mam na Gualainn, Beinn na Caillich and Sgor an Fhuarain. It is not intended in this summary to describe large scale structures such as those mapped by Bailey, although the orientation of the axes of some large folds is determined indirectly by statistical analysis; concern here is /

is with structures on a macroscopic scale. Also, in the interests of brevity, the results of studies on a microscopic scale are omitted from this work; and descriptions of structural features of rocks, and of diagrams showing preferred orientation of structural elements, are given in a brief and simplified form. In the next section the most important features of the penetrative structures on a macroscopic scale are briefly described, and, in the section after that, the results of the statistical analysis of these structures are summarized. In the concluding section a few preliminary conclusions of regional significance are drawn.

II. PENETRATIVE STRUCTURES

General statement: A small scale geological map of the West and Central Highlands of Scotland shows clearly the large "kink" in the generally north-east regional strike of foliation which appears in the metamorphic rocks of north-west Argyllshire, just to the south of the upper part of Loch Leven. When contrasted with the areas to the north and south (as far as can be judged from published accounts), another structural peculiarity of the rocks in the vicinity of Loch Leven, obvious to an observer in the field, is an abundance of fold axes and lineations showing complexity of form and variety of orientation, which remain unexplained by Bailey's structural synthesis. Bailey was no doubt aware of this when he wrote (Bailey, 1934, p. 465), with regard to the area immediately to the south of Loch Leven: "clearly, pre-existing folds have been bent wide-ways as well as downwards". The complexity of the structures leaves no doubt, as Bailey surmised, that the rocks of the area have more than one generation of fold-structures. Some of the rocks have several sets of lineations and most show development of more than one set of penetrative structural surfaces. The orientation and mutual relations of these axes /

axes and surfaces never have been satisfactorily described or explained.

It is easily established that the degree of structural complexity in the area is such that the symmetry of fabrics on most scales is triclinic and inhomogeneous with respect to most structural elements. The area has been divided into four smaller areas to reduce the degree of structural inhomogeneity. The first division into two areas is by the natural boundary of the Loch. This boundary corresponds roughly with the change in regional strike of foliation. A further division of each side of the Loch into two smaller areas, one to the west of the narrows at Calasnacon and one to the east, can be conveniently made. This division places the most massive body of quartzite in the area, the Glencoe quartzite, together with much of the Binnein quartzite, into the western areas (W_1 and W_2 , respectively, to the north and south of the Loch), and places the thickest layers of schist, the Binnein and Eilde schists, together with some thick layers of quartzite, into the eastern areas (E_1 and E_2 , respectively, to the north and south of the Loch). In the following sections the salient features of the penetrative structures of regional significance that can be distinguished in these areas are briefly described.

Structural surfaces: The dominant penetrative structural surface of the area is the foliation, which, in the quartzites, generally is parallel to sedimentary bedding. The current bedding of some of the quartzites is justly famous; an example from an impure micaceous quartzite at Rudha Cladaich (area W₁) is shown in plate 1. The presence of such well preserved sedimentary structures suggests that the quartzites have escaped internal strain. This is true on most scales for most of the quartzites, but, nevertheless, the quartzites are folded, and many bedding surfaces in even the most massive bodies have acted as surfaces of slip. This is not so true of the surfaces of current bedding, which are commonly not surfaces of mechanical weakness and do not have a constant orientation; rather it is the essentially planar surfaces of normal bedding separating the individual current bedded layers which have behaved as surfaces of slip during flexural slip folding. But in the thin quartzites within the layers of schist, and even at the margins of bodies of massive quartzite, surfaces of current bedding, if suitably oriented, have acted as surfaces of slip. Plate 2 shows an example in which penetrative slip on current bedding in the thicker layer of quartzite to the right of the plate has caused the angle between the current bedding /

bedding and the normal bedding, defined by the margin of the layer, to be increased.

Foliation in the schists also has, in general, a close relation to sedimentary bedding, demonstrated by the presence parallel to it of thin current bedded quartzites (plate 2 and plate 3). But the foliation in the schist is in many places a surface of intense penetrative slip and flexural slip, and is locally a structure produced by transposition of bedding. The complex relations between schist and thin layers of quartzite which can arise in this fashion are demonstrated by plate 4, which shows folded and shredded layers of intensely internally deformed quartzite floating in Binnein schist on the small hill Torr a'Phloda at Calasnacon (area E₂). A still more advanced stage of deformation on a smaller scale is shown in plate 5 from the Eilde schists in the east of area E₂. The light-coloured layers are disrupted lenticles of mixed quartzite and vein quartz, torn apart by folding and transposition, embedded in a matrix of complexly folded and sheared mica schist. These plates demonstrate the errors which could arise from the use of stratigraphical criteria in ~~the~~ examining both the variation in thickness of individual layers of schist, and the significance of contacts between schist and quartzite. /

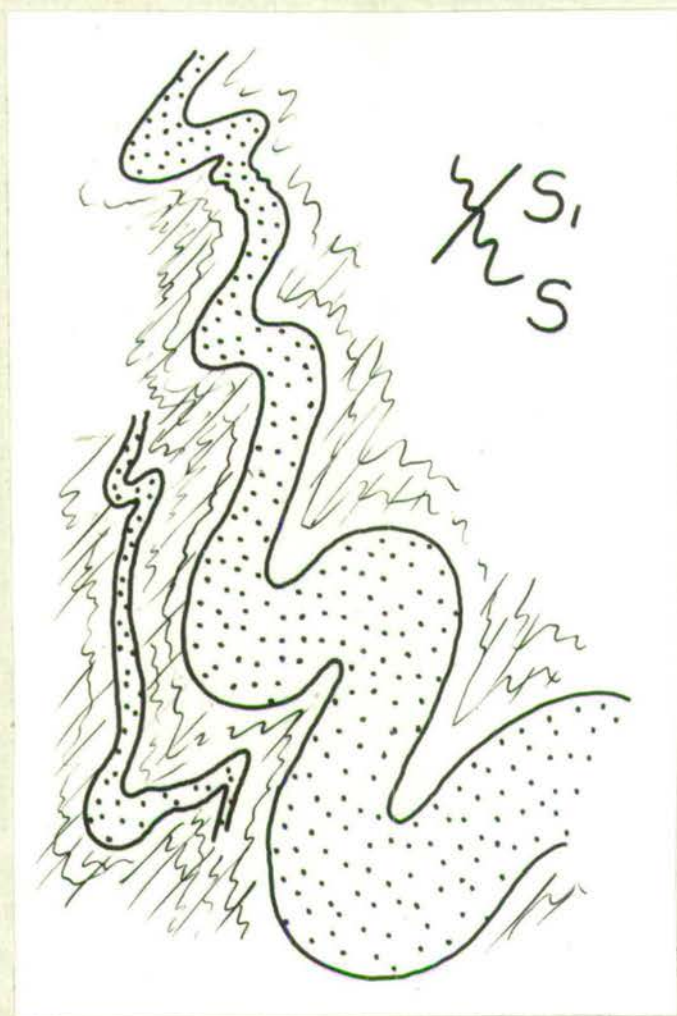


Figure 1. Foliation (S) folded about B with S₁ parallel to axial surface of folds.

quartzite. The differential behaviour of the two rock types during deformation means that every contact between quartzite and schist and every foliation surface in the schists is a tectonic contact or "slide". The internal and external form of the schists on a large scale has been greatly modified by penetrative movement, if the visible strain on a small scale is to be taken as a guide to overall deformation.

The foliation (that is, the differential layering) of the area is thus in part sedimentary bedding and in part sedimentary bedding much modified by deformation. Whatever its origin, this foliation is here termed S to distinguish it from two other penetrative structural surfaces distinguishable in the area, as follows:

1. Where S in the schists is folded about one group of moderately plunging fold axes (E - see below) a fine fissility is locally developed parallel to the axial planes of the folds. In figure 1, drawn from an exposure in Binnein schist on Torr nan Crann (area E₂) this surface is labelled S₁. In its weakest development, in thin schists in quartzite, it is subordinate to S and does not appear to be an important surface of slip, rather, it resembles slaty cleavage; but in the thicker layers of schist it is an obvious surface of slip and produces /

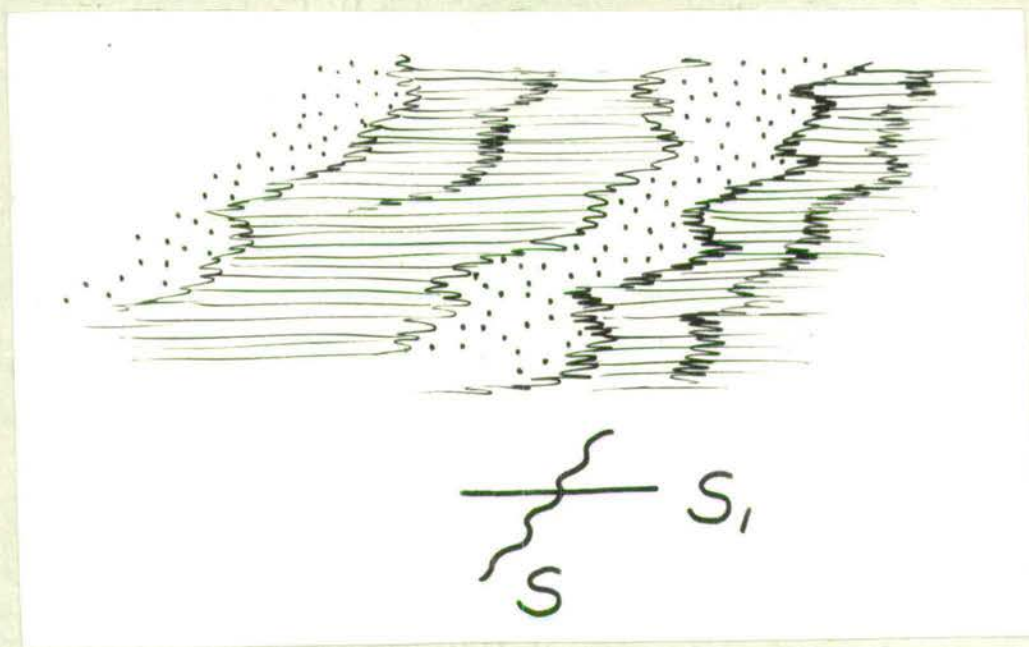


Figure 2. Shear folding of incompetent layers parallel to \underline{S} by slip on \underline{S}_1 .

produces shear folding of passive layers parallel to \underline{S} (figure 2, drawn from Binnein schist a mile east of the narrows in area E_1), and, in limit, transposition of \underline{S} . The two sets of surfaces \underline{S} and \underline{S}_1 have both acted as slip surfaces in the phase of deformation that produced the folds in question, \underline{S} as a surface of flexural slip, and \underline{S}_1 as a surface of slip. It has already been pointed out that some of the foliation (\underline{S}) in the schists has been produced by transposition of sedimentary bedding, in \underline{S}_1 this process is seen in its initial stages. Thus, \underline{S} and \underline{S}_1 can be mutually distinguished in the schists only where \underline{S}_1 is weakly developed or where transposition of \underline{S} is incomplete.

2. The second set of penetrative surfaces (here called \underline{S}') is genetically unrelated to \underline{S} , \underline{S}_1 and the folds with axes \underline{B} , to be described below. Throughout the area it shows a sequence of development, as follows:

- a. In its weakest development, \underline{S}' is defined by the short limbs of minute regular asymmetrical wrinkles in mica schist.
- b. With progressive deformation, these short limbs are replaced by surfaces of slip and a "strain-slip cleavage" is formed.
- c. The final stage is reached where slip on \underline{S}' becomes pronounced and a new planar foliation is formed almost indistinguishable from \underline{S} and \underline{S}_1 .

In /

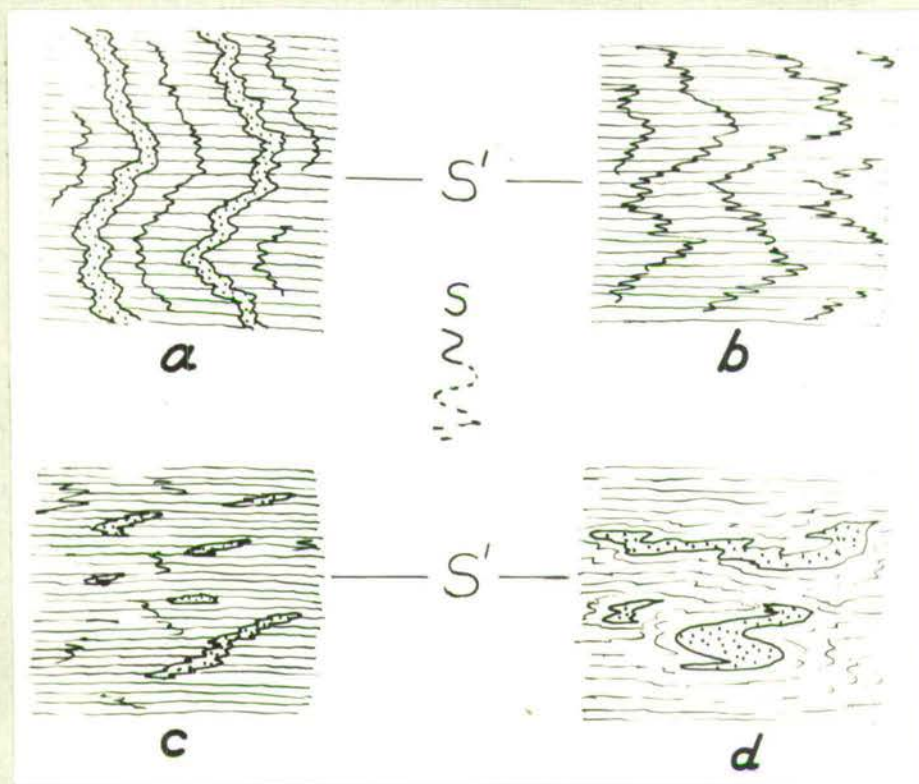


Figure 3. Transposition of S by slip on S' .

In the early stages of its development \underline{S}' cannot be mistaken for \underline{S}_1 because it never resembles slaty cleavage. But it is locally associated with folds in \underline{S} or \underline{S}_1 homologous on a large scale with the minute wrinkles mentioned in a, above. \underline{S}' is parallel to the axial planes of these folds. In figure 3 is shown diagrammatically a sequence of development of \underline{S}' from a "strain-slip cleavage" parallel to the axial planes of syngenetic folds in \underline{S} (figure 3a), through a stage of shear folding of \underline{S} (figure 3b) and a stage of disruption of competent layers parallel to \underline{S} (figure 3c), to a final stage of complete transposition of \underline{S} in which even disrupted fragments of competent layers are rotated into conformity with \underline{S}' (figure 3d). The folds associated with \underline{S}' are not to be confused with the \underline{B} -folds, mentioned above, with axes parallel to the intersection of \underline{S} and \underline{S}_1 . Where \underline{S}' occurs with \underline{B} -folds it usually intersects \underline{B} at a very high angle, and is never parallel to the axial surfaces of these folds. In figure 4 is shown part of a \underline{B} -fold where \underline{S} is parallel to a boundary between quartzite and mica schist. \underline{S}' is developed almost normal to \underline{B} . In the mica schists it is a "strain-slip cleavage" whereas in the quartzite it is defined by no visible surface but is nevertheless present in some form because its intersection /

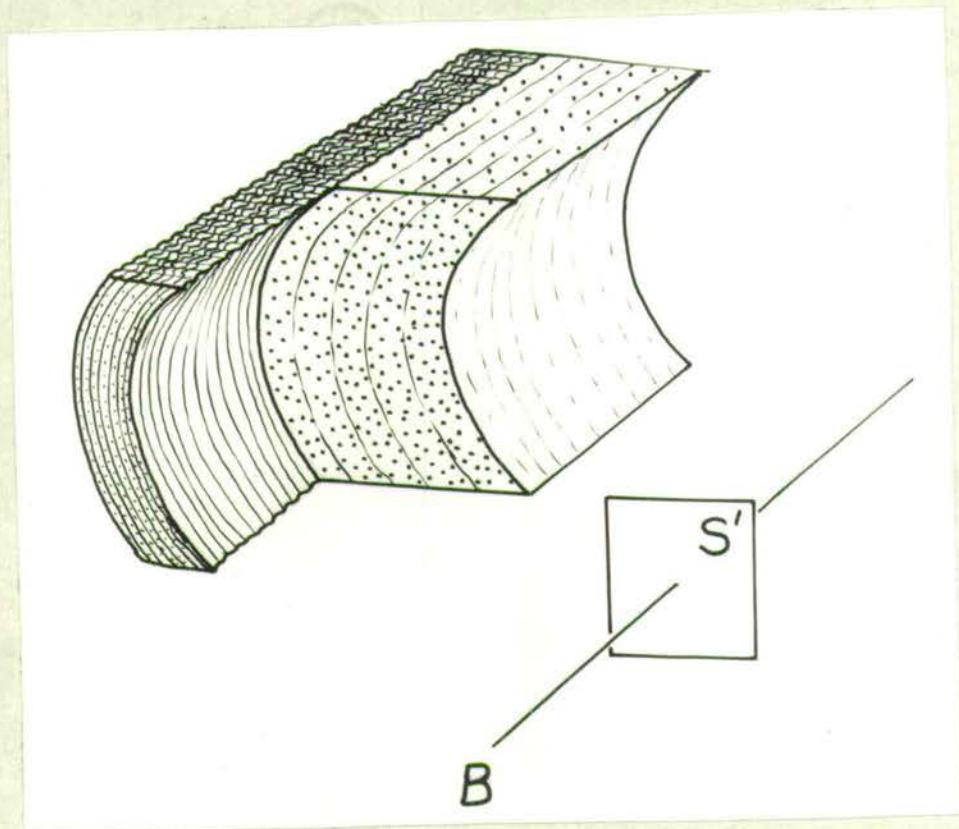


Figure 4. S' intersecting S folded about B.

intersection with \underline{S} is defined by a faint lineation. Where \underline{S}' is associated with large scale syngenetic shear folding of \underline{S} it produces bending of the axes (\underline{B}) of previously formed folds in \underline{S} , as shown diagrammatically in figure 5. A lineation and an axis of small scale folding mark the intersection of \underline{S}' with \underline{S} around the \underline{B} -fold as shown diagrammatically by the line \underline{B}' . This lineation always lies in the plane of \underline{S}' but it varies in plunge and, if \underline{S}' is not vertical, in trend, according to the point on the \underline{B} -fold at which measurement is made. Structural relations such as these leave no doubt that \underline{S}' formed after the \underline{B} -folds and thus after the formation of \underline{S} (where this is a shear foliation) and \underline{S}_1 ; they also demonstrate that more than one generation of axial structures exists in the area.

Structural axes: Three main categories of fold in \underline{S} can be distinguished in the area, on the basis of style and orientation, as follows:

1. The aforementioned folds with axes \underline{B} are easily distinguished from the other kinds on the basis of their style. Present in all rocks, they are mostly recumbent about moderately plunging axes, and range in size from small folds of the kind shown in plate 3, through folds of intermediate size as shown in /

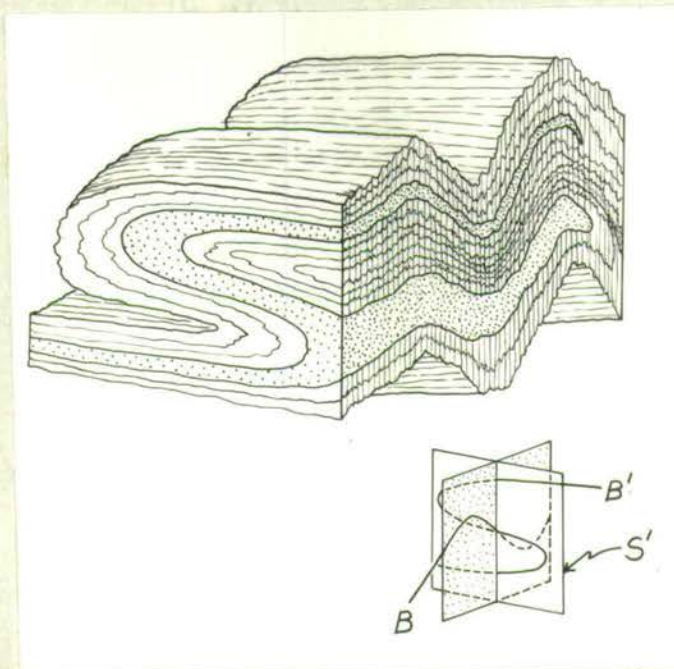


Figure 5. B-fold shear folded by slip on S'.

in plates 4 and 6 (thick quartzite in Eilde schist in the east of area E_2) to large recumbent folds many hundreds of feet in amplitude some of which, like these exposed in the Binnein quartzite on Sgòr an Fhuarain, are closely appressed. Although the plunge of the axes of these E -folds generally is small, the trend varies greatly. In the quartzites, the folds are cylindroidal on a macroscopic scale, but, in the schists, the fold axes are sinuous on even a small scale. Where the surface S_1 is developed, it is parallel to the axial surfaces of these folds, as described above. They are the earliest developed folds of the area and are no doubt homologous with the very large scale folds mapped by Bailey. All other structures are superposed upon them.

2. In the areas W_1 and W_2 , folds of various sizes occur with axes plunging regularly and steeply to the west. The largest of these folds locally resemble the E -folds but are distinguished from them by the regular and steep plunge of their axes (here termed E'). In suitably oriented S -surfaces the E' -folds can be found superposed upon previously formed E -folds. They are genetically related to the third type of fold.

3. In areas E_1 and E_2 small folds in S are present in great profusion /

profusion, with axes parallel to the intersection of \underline{S} and \underline{S}' . The trend of these folds is fairly constant, between north-east and east, but the plunge can have any value in either sense. Some of the folds are flexural slip folds and some are slip folds; and the axes ($\underline{S} \times \underline{S}'$) of most of the folds plunge, like the \underline{B}' -axes of areas W_1 and W_2 , steeply to the west and are superposed upon the earlier \underline{B} -folds, as shown in figures 4 and 5.

On grounds of symmetry, the axes of all the flexural slip folds (\underline{B} , \underline{B}' and $\underline{S} \times \underline{S}'$) are \underline{B} -axes. But, as can be seen from figure 5, not all the $\underline{S} \times \underline{S}'$ folds are \underline{B} -axes. If slip on \underline{S}' is in constant sense (normal to the kinematic \underline{B} -axis) then the curved fold axis labelled \underline{B}' in figure 5 cannot everywhere be parallel to the kinematic \underline{B} -axis. Folds produced in this way are slip folds and do not have overall monoclinic symmetry of fabric.

The axes of all three types of fold may be paralalled by lineations of various kinds, most of which are \underline{B} -lineations; but lineations, in the area as a whole, are much more variable in orientation than folds and most rocks show development of impersistent and locally irregular lineations. These lineations indicate the presence of sporadically developed flow surfaces, suggesting local variation of the movement picture during deformation /

deformation. The exposure shown in plate 7 (near Allt Nath-rach in area E_1) is of a foliation surface (\underline{S}) with many lineations oriented in different directions. In the rock concerned, at least four penetrative structural surfaces can be recognized by microscopic structural analysis, namely \underline{S} , \underline{S}_1 , \underline{S}' and another surface \underline{S}'' genetically related to \underline{S}' . The mutual intersection of these surfaces give a three dimensional framework of structural axes which together with their projection-traces have a geometry of great complexity. The geometry of such fabrics can be fully established only by detailed analyses on macroscopic and microscopic scales and is beyond the scope of this summary. But these locally developed lineations, and other structural complexities, when statistically evaluated on a large scale, are insignificant in the geometry of the whole area; the only axes of regional significance are \underline{E} , \underline{E}' and $\underline{S} \times \underline{S}'$.

III. STATISTICAL ANALYSIS

General statement: Procedure in structural analysis followed in the present investigation is the same as that outlined by the writer for the Turoka area in Kenya (Weiss, 1956). The inhomogeneous eastern areas have been subdivided into sub-areas with greater structural homogeneity with respect to selected structural elements. All data shown in figures 6 to 8 and maps 1 and 2 are plotted on the lower hemisphere of an equal area projection. The only structural elements considered in this summary are \underline{S}_1 , \underline{E} , \underline{B}' , \underline{S}' and $\underline{S} \times \underline{S}'$.

\underline{S} : Figure 6a shows all $\Pi \underline{S}$ -poles measured in the four areas. The poles lie in a broad girdle defining a β -axis for the whole area plunging at about 45° to the north-west. Because this β -axis corresponds to no generally observed fold within the area, it must be concluded that it is a "pseudo β -axis" resulting from the fortuitous arrangement of $\Pi \underline{S}$ -poles measured in a field with overall structural inhomogeneity with respect to a single axis of folding. If the $\Pi \underline{S}$ -poles for areas E_1 , W_1 and areas E_2 , W_2 , are plotted separately (respectively, figures 6b and 6c), the change in strike of \underline{S} across the Loch is clearly expressed in the diagrams; but each diagram still faintly defines the "pseudo β -axis" of figure 6a.

From /

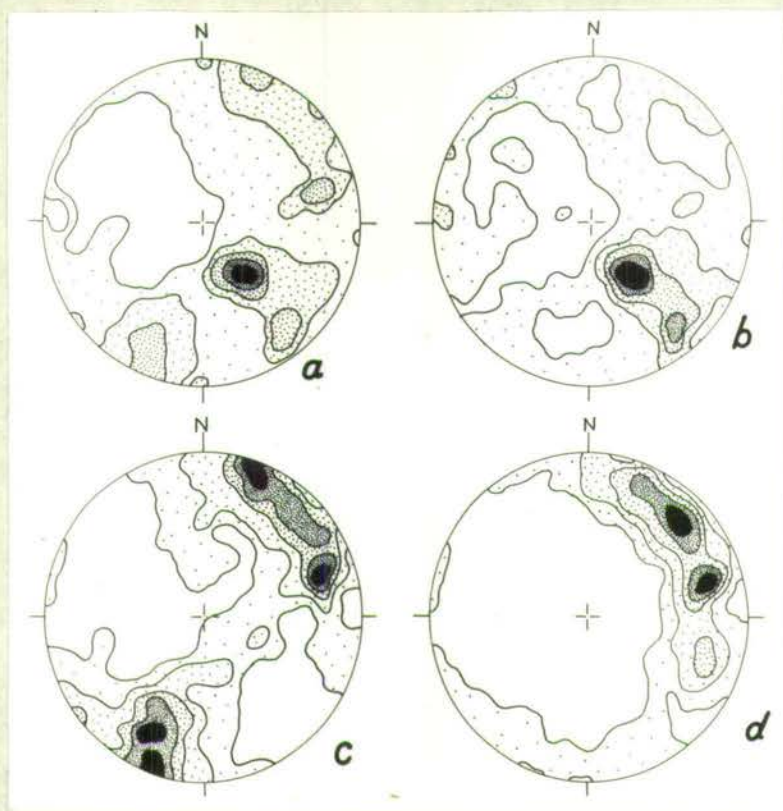


Figure 6. Synoptic diagrams for π S-poles.

- a. 791 poles measured in whole area;
contours, 1-2-3-4-5% per 1% area.
- b. 285 poles measured in areas W_1 and E_1 ;
contours, 1-3-5-7-9% per 1% area.
- c. 408 poles measured in areas W_2 and E_2 ;
contours, 1-2-3-4-5% per 1% area.
- d. 205 poles measured in areas W_1 and W_2 ;
contours, 1-3-5-7-9% per 1% area.

From the study of folds in the field it was established that the two western areas showed a high degree of homogeneity with respect to orientation of small folds and lineation parallel to the axis \underline{B}' , and so Π S-poles for areas W_1 and W_2 have been plotted together in figure 6d. A very clearly formed girdle emerges defining a β -axis (β') corresponding broadly with the orientation of \underline{B}' -structures. The areas W_1 and W_2 are homogeneous on all scales with respect to \underline{B}' (β'), and the form of the great body of Glencoe quartzite is a large single fold closing westwards with small folds and lineations on the limbs parallel to its axis (\underline{B}'). There is no evidence in figure 6d that Π S- in areas W_1 and W_2 is folded about any axis other than \underline{B}' , but observation, in the field, of \underline{B} -folds with shallow plunge and variable trend proves this to be untrue. However, the folds about \underline{B} must have been either very weak or recumbent and closely appressed, otherwise it would have been impossible for the quartzite to have the form of the great uniformly dipping sheet it must have had before the movements that produced the regularly plunging flexural slip folds about \underline{B}' .

The remaining Π S-poles show no simple preferred orientation in either E_1 or E_2 and it must be concluded that these areas are structurally inhomogeneous with respect to any single /

single fold axis. On the basis of field investigation, areas E_1 and E_2 have been divided into 20 subareas as shown in maps 1 and 2. Each projection on the maps shows data measured in the vicinity of the projection. In general, a projection centred in a layer of schist shows measurements made in that particular layer of schist. Similarly, a diagram superposed on an area of quartzite shows data measured in that particular outcrop of quartzite. Measurements were made over the whole area shown in the map with, where exposure permitted, approximately uniform distribution.

In most of the subareas the Π S-poles define clear β -axes (β), but the orientation of these axes varies from subarea to subarea. The exceptions are subareas 1, 7, 8, 9 and 15, most of which are from thick layers of schist with little quartzite. These layers are structurally inhomogeneous on all scales (some even on a microscopic scale) because of strong development of S' and $S \times S'$ -folds and lineation. The area of map 1 can be divided into two areas of homogeneity, with respect to the trend of β , by the thick broken line. This division shifts some of the southern part of area E_1 into area E_2 . To the north of this line the trend of β is approximately north-east, to the south the trend is approximately north-west ;/

north-west; and this change in orientation of β coincides in amount and location with the change in strike of \underline{S} mapped by Bailey. There can be no doubt that \underline{S} was folded about \underline{B} before the movements occurred which caused the "kink" in the regional strike at Loch Leven.

The β -axis defined by $\Pi \underline{S}$ -poles in subareas 19 and 20 of map 1 is the β' -axis of area W_2 to which these subareas are immediately adjacent and structurally related.

B and B': All axial structures measured in areas E_1 , E_2 , W_1 and W_2 are shown in figure 7a. They lie in a broad girdle striking roughly east to west with a strong maximum plunging at 60° west. If the $\underline{S} \times \underline{S}'$ -structures of areas E_1 and E_2 are removed from this diagram it appears as in figure 7b. The maximum, which still does not coincide with the "pseudo β -axis" of figure 6a, has become more pronounced and agrees closely with the β' -axis of figure 6d (areas W_1 and W_2). The \underline{B}' -structures for these areas, when plotted separately, appear as in figure 7c and have a very high degree of preferred orientation: the maximum agrees exactly with the β' -axis of figure 6d, confirming the structural homogeneity on all scales of areas W_1 and W_2 with respect to \underline{B}' . When the \underline{B}' -structures are /

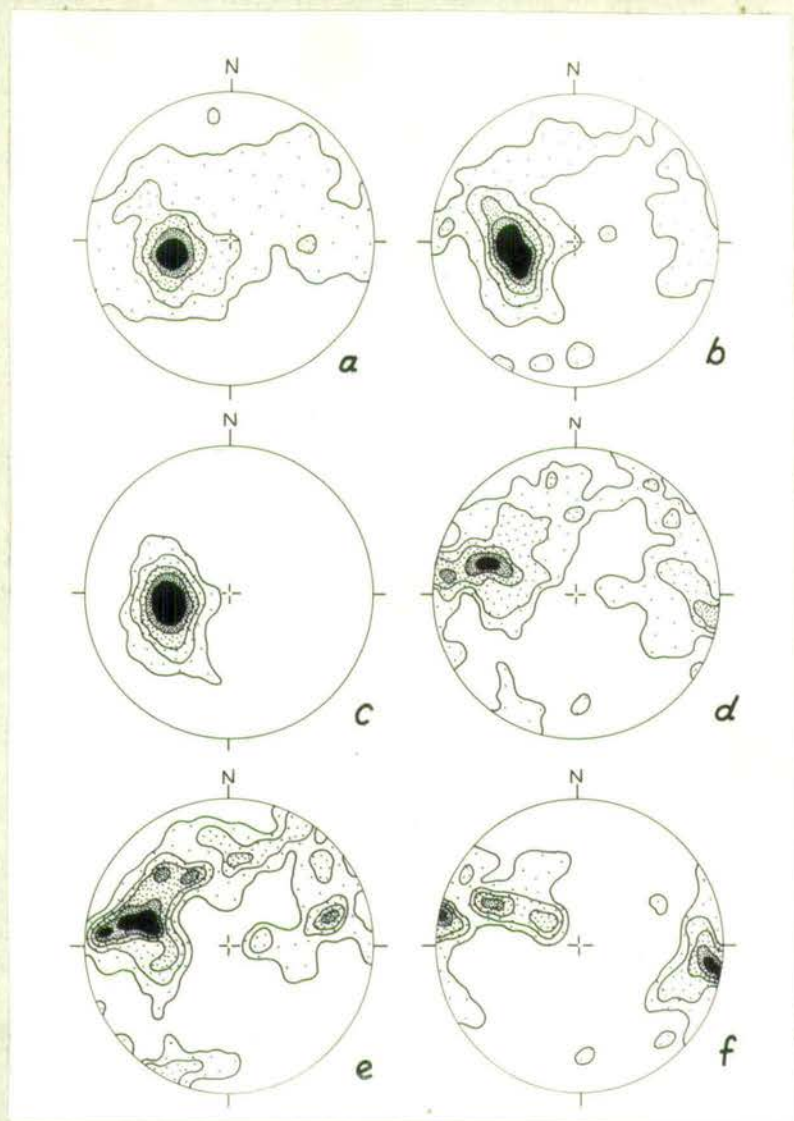


Figure 7. Synoptic diagrams for axial structures.

- a. 523 \underline{B} -axes measured in the whole area; contours, 1-3-5-7-9% per 1% area.
- b. 250 \underline{B} - and \underline{B}' -axes measured in the whole area; contours, 1-3-5-7-9% per 1% area.
- c. 118 \underline{B}' -axes measured in areas W_1 and W_2 ; contours, 1-5-10-15-20% per 1% area.
- d. 126 \underline{B} -axes measured in whole area; contours, 1-3-5-7-9% per 1% area.
- e. 87 \underline{B} -axes measured in areas W_1 and E_1 ; contours, 1-2-3-4-5% per 1% area.
- f. 41 \underline{B} -axes measured in areas W_2 and E_2 ; contours, 2-4-6-8-10% per 1% area.

are removed from figure 7b the resultant synoptic diagram is as in figure 7d. The measurements that remain are for E-folds and lineations measured mostly in areas E_1 and E_2 . A further subdivision of this diagram gives patterns for E_1 and E_2 as shown respectively in figures 7e and 7f. The first of these is obviously inhomogeneous with respect to B, the second is less so. In map 1, the orientation of B-structures is shown in each of the subareas used for plotting ΠS . In most of the subareas homogeneous with respect to β , the E-folds show a preferred orientation close to β confirming the common origin of the structures. B and β are homologous structures on different scales. The change in trend of β occurring to the north and south of the broken line is exactly mirrored by a change in trend of B.

In subareas 1, 7 and 9, the distribution of B-structures shows these areas to be structurally inhomogeneous with respect to B on all scales. The spread of B-structures seen in the diagrams for these subareas corresponds broadly in form to the spread of B-structures in the whole of areas E_1 and E_2 as expressed in figure 7d. The inhomogeneity of the subareas is homologous with the inhomogeneity of the whole of areas E_1 and E_2 and arises from the same cause; the only difference between the phenomena is in scale.

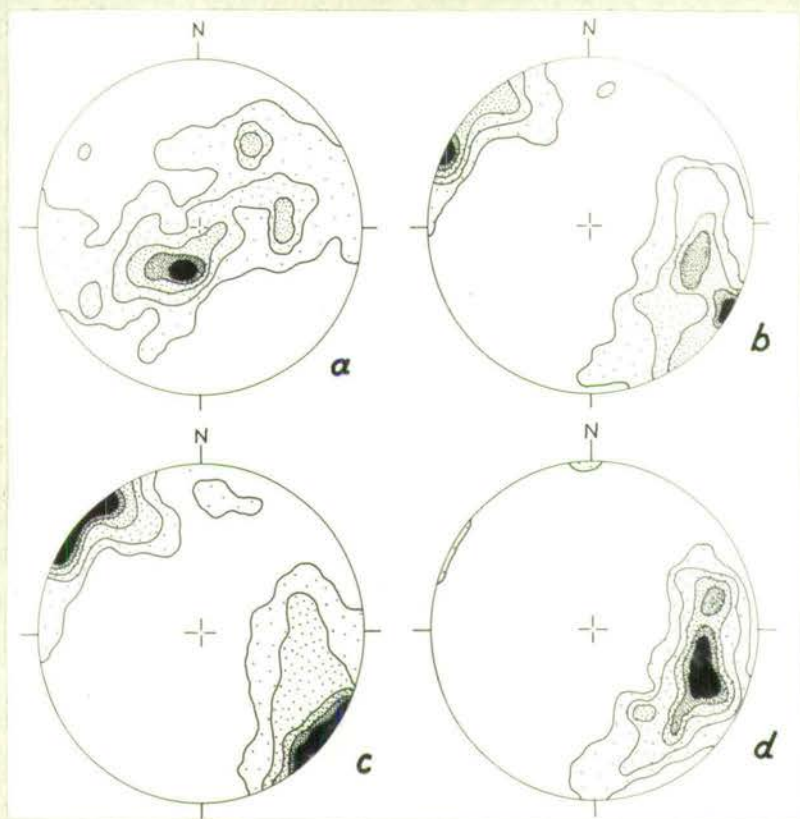


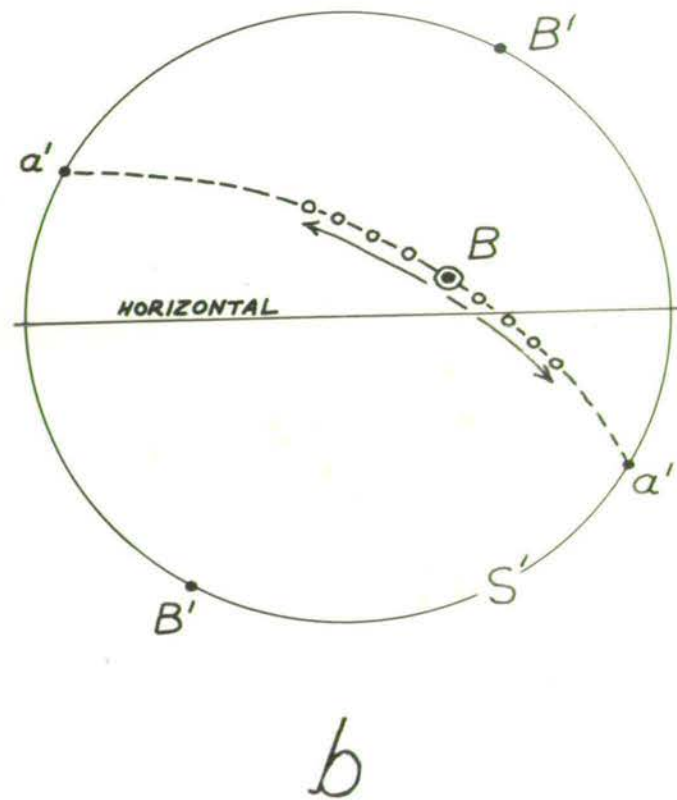
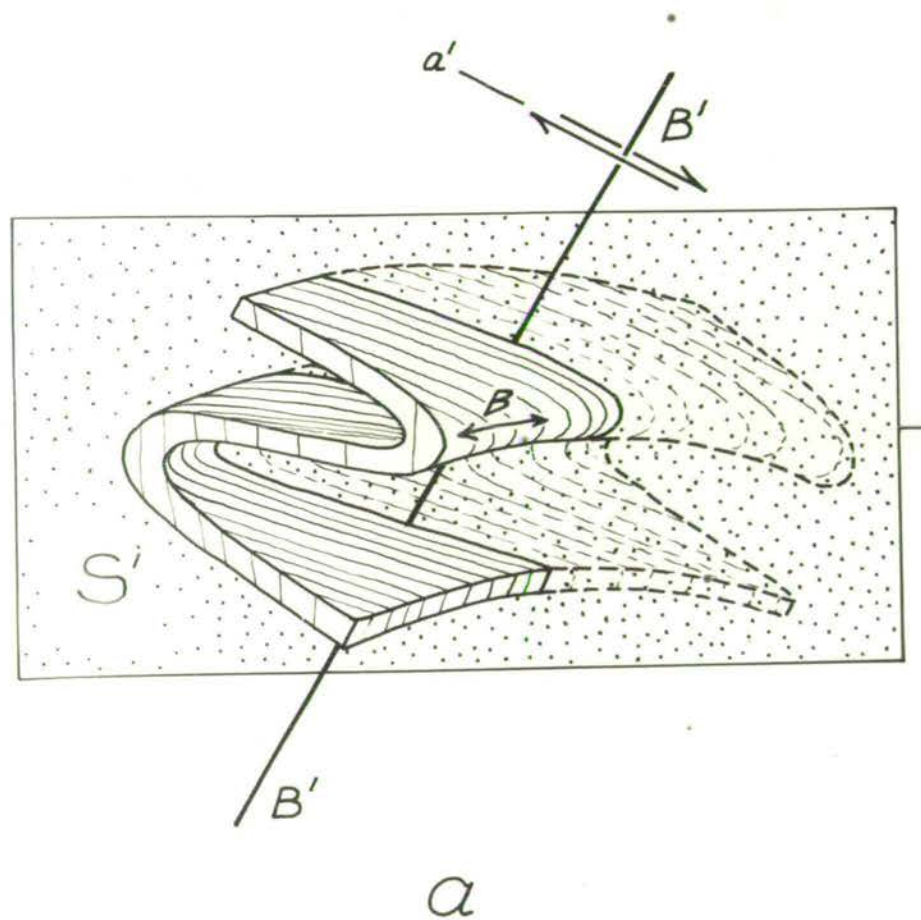
Figure 8. Synoptic diagrams for $\underline{S} \times \underline{S}'$ and \underline{S}' .

- a. 191 $\underline{S} \times \underline{S}'$ -axes measured in areas E_1 and E_2 ;
contours, 1-3-5-7-9% per 1% area.
- b. 239 \underline{S}' -poles measured in areas E_1 and E_2 ;
contours, 1-3-5-7-9 % per 1% area.
- c. 152 \underline{S}' -poles measured in area E_1 ;
contours, 1-3-5-7-9% per 1% area.
- d. 87 \underline{S}' -poles measured in area E_2 ;
contours, 1-3-5-7-9% per 1% area.

S X S' and S': The orientation of all S X S'-folds and lineations taken from figure 7a is shown in figure 8a. They lie in a marked girdle with a single steeply plunging maximum. The orientation of S' in areas E_1 and E_2 is shown in figure 8b. Irrespective of the structural inhomogeneity of these areas with respect to B and S, S' has a strikingly constant orientation. There is little difference in the orientation of S' between areas E_1 and E_2 as can be seen respectively from figures 8c and 8d. Because S was folded about B before the formation of S', S' can intersect S at any angle and the S X S' structures must lie in the regional statistical preferred orientation of S'. This relationship is expressed in the girdle of S X S'-axes (figure 8a) oriented roughly normal to the maximum of Π S'-poles (figure 8b). The maximum in figure 8a indicates that, before S' was formed, S had a preferred orientation containing this direction.

In map 2 the orientations of S X S' and S' are shown in the twenty subareas. These structures are most strongly developed in the zone where the change in strike of S occurs (for instance, see subareas 1, 4, 7, 12 and 18) and it must be concluded that S' (and, consequently, also the S X S'-structures) were formed at the same time as the fold axis B and the regional strike /

strike of \underline{S} were rotated almost through a right angle in the vicinity of the Loch. The \underline{B}' -structures of the western areas were formed at the same time and are homologous with the $\underline{S} \times \underline{S}'$ -structures. The uniform orientation of \underline{B}' in the western areas, when compared with the orientation of $\underline{S} \times \underline{S}'$ in the eastern areas, indicates a uniform orientation of \underline{S} in the western areas before the formation of \underline{B}' ; \underline{S} must have been oriented with a statistically uniform dip (although folded about \underline{B}), and \underline{B}' formed parallel to the statistically linear intersection of \underline{S} with \underline{S}' . The movements that produced \underline{B}' in the regularly dipping layers of quartzite in areas W_1 and W_2 produced a girdle of $\underline{S} \times \underline{S}'$ -structures in the more strongly folded schists of areas E_1 and E_2 . Some of the $\underline{S} \times \underline{S}'$ -structures are \underline{B} -axes but others are not. In figure 9 is shown diagrammatically a \underline{B} -fold in subarea 1 internally rotated by non-affine slip on \underline{S}' . This subarea is squeezed below the great arch of quartzite of the western areas, and the slip on \underline{S}' is normal to \underline{B}' , the axis of the arch. The internally rotated \underline{B} -axis follows the path shown in the projection (see Weiss, 1955, pp. 228-229). The spread of \underline{B} shown in subarea 1 is in part a result of this kind of internal rotation and in part a product of irregular flexural slip on \underline{S} . The \underline{B} -folds which /



which survive in this and other similar subareas (especially 7 and 18) have very complex geometry, on even a small scale, and are not sufficiently cylindroidal for their axes to be measured.

IV. CONCLUSIONS

Two distinct generations of structures can be recognized in the rocks of Loch Leven, as follows:

1. The earliest formed folds in the area are homologous with the great folds mapped by Bailey; to the north of the broken line shown on maps 1 and 2, which corresponds in part with the Loch, the trend of this axis (B) is north or north-east; to the south of the broken line, the trend is to the south-east. From the structural features of the neighbouring areas it must be assumed that the trend of B before the Loch Leven "kink" was formed was north or north-east, as it appears to remain in much of the area to the north of the Loch. Kinetically, these B-folds can be correlated with an axis of greatest principal strain (P) lying in a plane normal to B, striking roughly north-west and dipping steeply or vertically.

2. Folds and lineations in S occur statistically oriented in a plane striking west-south-west and dipping steeply or vertically. The axes of these folds are parallel to the intersection between S (folded about B) and a surface S'. In the western part of the area, the fold axes are B-axes (B') and plunge uniformly and steeply to the west. To the east of the /

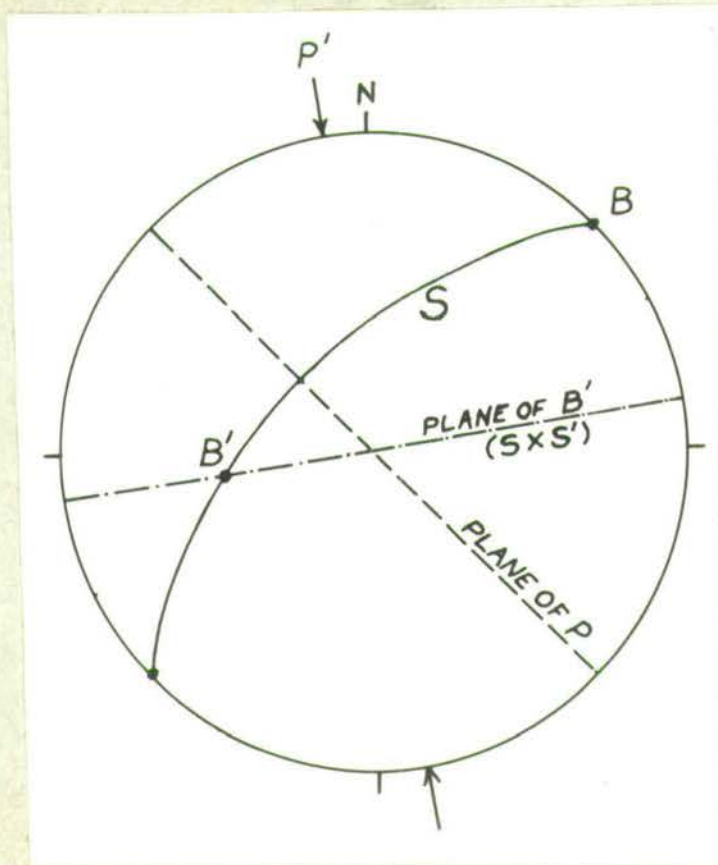


Figure 10. Synopsis of structural elements in the Loch Leven area (explanation in text).

the great sheet of Glencoe quartzite, the schists and thinner quartzites were more closely folded about \underline{E} , and \underline{S}' intersects \underline{S} at a variety of angles. The greatest complications occur in the thick layers of schist where the axes of \underline{E} -folds are bent on a very small scale. Some of the $\underline{S} \times \underline{S}'$ -folds have axes which are \underline{E} -axes (also labelled \underline{E}'); but others are slip folds with axes that are not \underline{E} -axes. The statistically defined plane \underline{S}' corresponds to a \underline{E}' -plane (see Weiss, 1956) normal to which is an axis of greatest principal strain (\underline{P}'). This axis trends north-north-west and thus is oblique to the plane of \underline{P} . The overall geometry of movement and fabric in the area is shown in figure 10. \underline{E} is shown as horizontal and trending north-east. The axis of greatest principal strain in the first phase of movement is in the plane of \underline{P} . The axis of greatest principal strain in the second phase of movement is \underline{P}' normal to which is the plane (\underline{S}') of \underline{E}' -structures ($\underline{S} \times \underline{S}'$). The preferred orientation of \underline{S} before the second phase of movement is responsible for the observed maximum of \underline{E}' -structures with a steep westerly plunge (\underline{E}' in figure 10). For the general case \underline{E}' is oblique to \underline{E} and the triclinic symmetry of the area seems to be a result of $\underline{E} \wedge \underline{E}'$ tectonics (superposed unrelated monoclinic strains) rather than $\underline{E} \perp \underline{E}'$ -tectonics (a single triclinic strain).

In /

In figure 11 is summarized in a very diagrammatic form the structural relation between quartzite and schist in the area of upper Loch Leven. The great body of quartzite in the left of the diagram represents the Glencoe quartzite of areas W_1 and W_2 weakly folded about \underline{B} (shown as horizontal). The schists and thinner quartzites of areas E_1 and E_2 are represented by the more closely folded rocks to the left of figure 11. Squeezing normal to \underline{S}' folds the Glencoe quartzite in the fashion shown in the block diagram so that it forms a great westward plunging arch with minor flexural slip folds and lineations on its limbs. The schists in the core of this arch are either folded by flexural slip of \underline{S} about axes lying in the plane normal to the axis of squeezing, or they fail by slip on \underline{S}' producing slip folds of \underline{S} . The direction of slip in \underline{S}' , where \underline{S} is slip folded, is decided by the axis (\underline{B}') of the great arch of quartzite. \underline{S}' may be looked upon as a shear foliation arranged in a fan roughly centred on the axial surface (the trace of which is given by the broken line in maps 1 and 2) of a great plunging fold (\underline{B}'). The fan-like form of \underline{S}' on either side of the axial surface is indicated in figures 8c and 8d.

It is unlikely that the second phase of movement which /

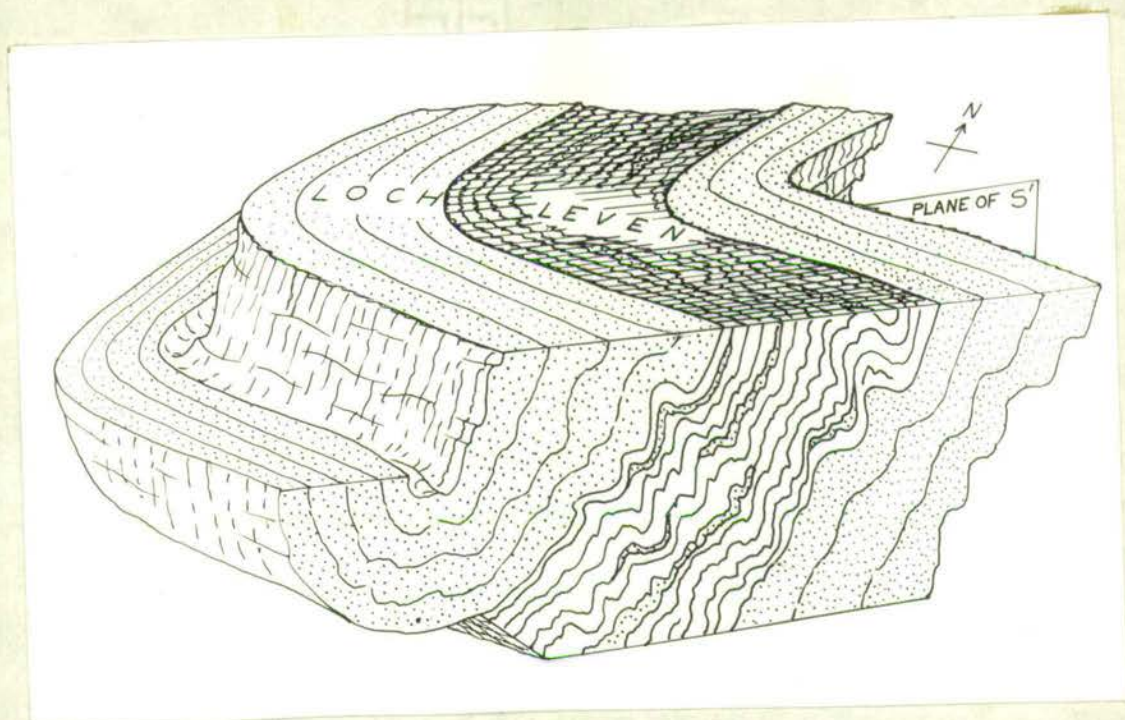


Figure 11. Diagrammatical representation of the structural relations between quartzite (stippled) and schist by upper Loch Leven.

which has modified the "Caledonoid" E-folds is confined to the neighbourhood of Loch Leven. The irregular sinuous outcrops of the formations to the north and south suggest that later structures may be superposed upon the earlier north or north-easterly trending folds over a wide area.

THE

SPECIAL

ROYAL EDWARD

PLATES and MAPS.



Plate 1. Current bedding in micaceous quartzite at
Rudha Cladaich (area W_1).



Plate 2. Slip on current bedding in folded quartzite
at margin of Binnein quartzite on Torran nan
Crann (area E₂).



Plate 3. Quartzitic layers folded about E in Binnein schist, west of Calasnacon (area W_2).

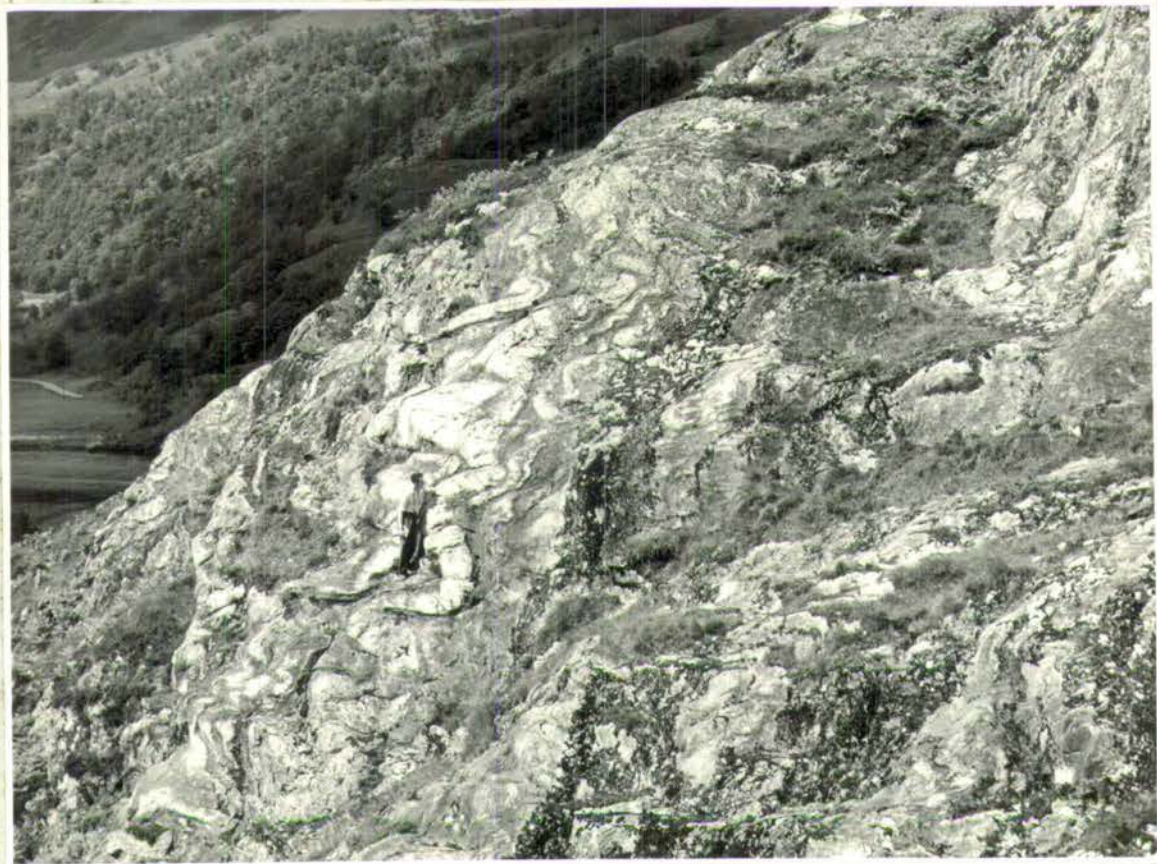


Plate 4. Intensely folded quartzitic lenticles in
Binnein schist on Torr a' Phloda (area E₂).



Plate 5. Disrupted quartzose lenticles in Eilde schist (area E₂).

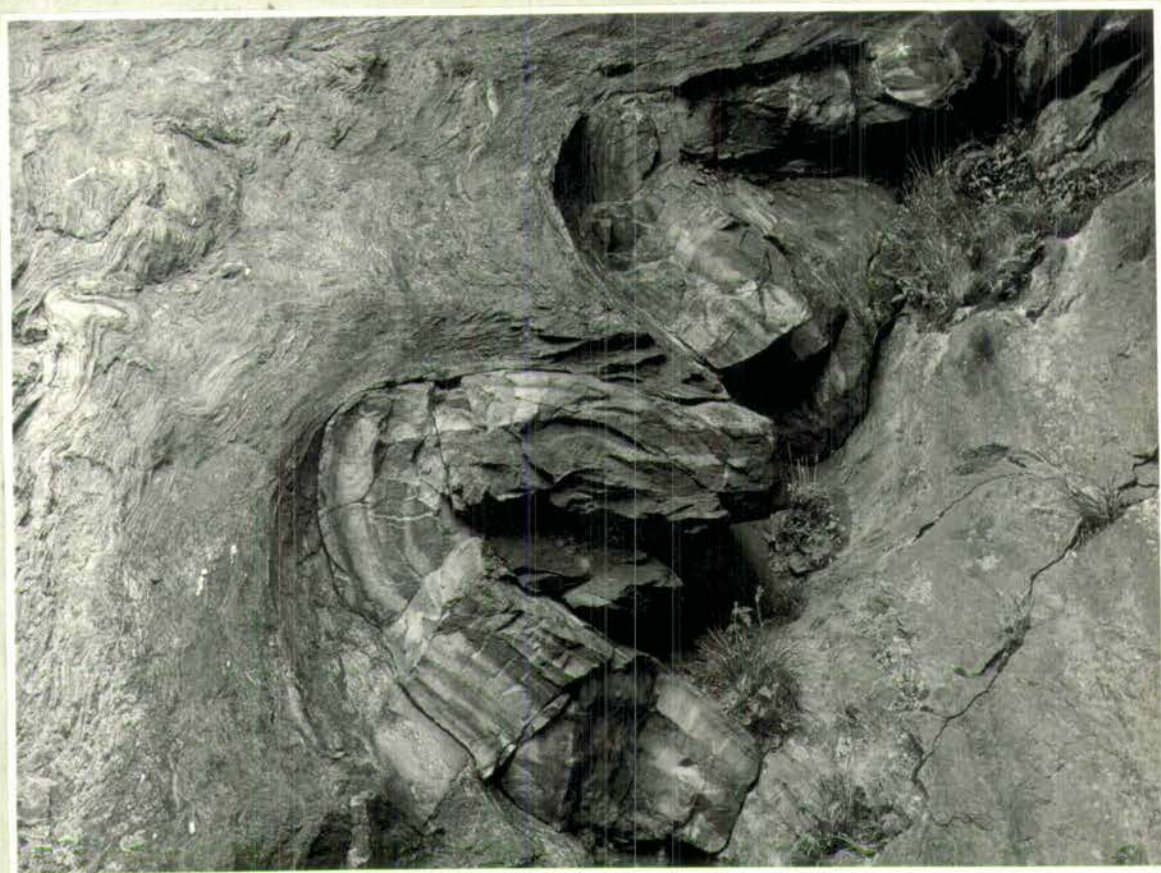


Plate 6. Large B-folds of quartzite layer in Eilde schist (area E_2).



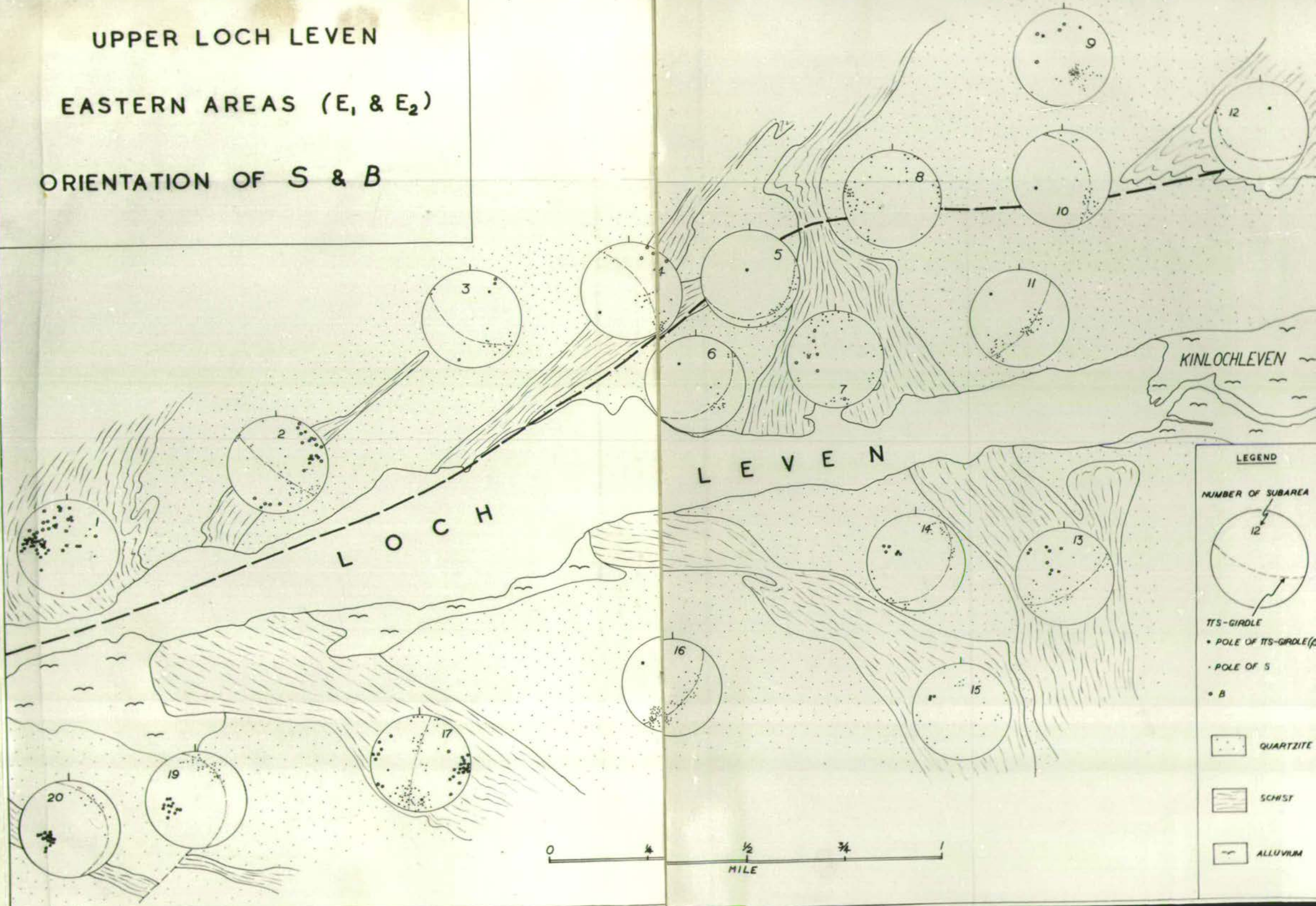
Plate 7. Complexly lineated mica schists near Allt
Nathrach (area E₁).

Map 1. Explanation in text.

UPPER LOCH LEVEN

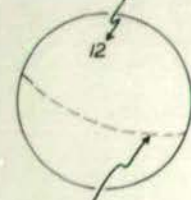
EASTERN AREAS (E₁ & E₂)

ORIENTATION OF S & B



LEGEND

NUMBER OF SUBAREA



TTS-GIRDLE

• POLE OF TTS-GIRDLE

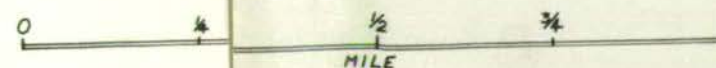
• POLE OF S

• B

QUARTZITE

SCHIST

ALLUVIUM

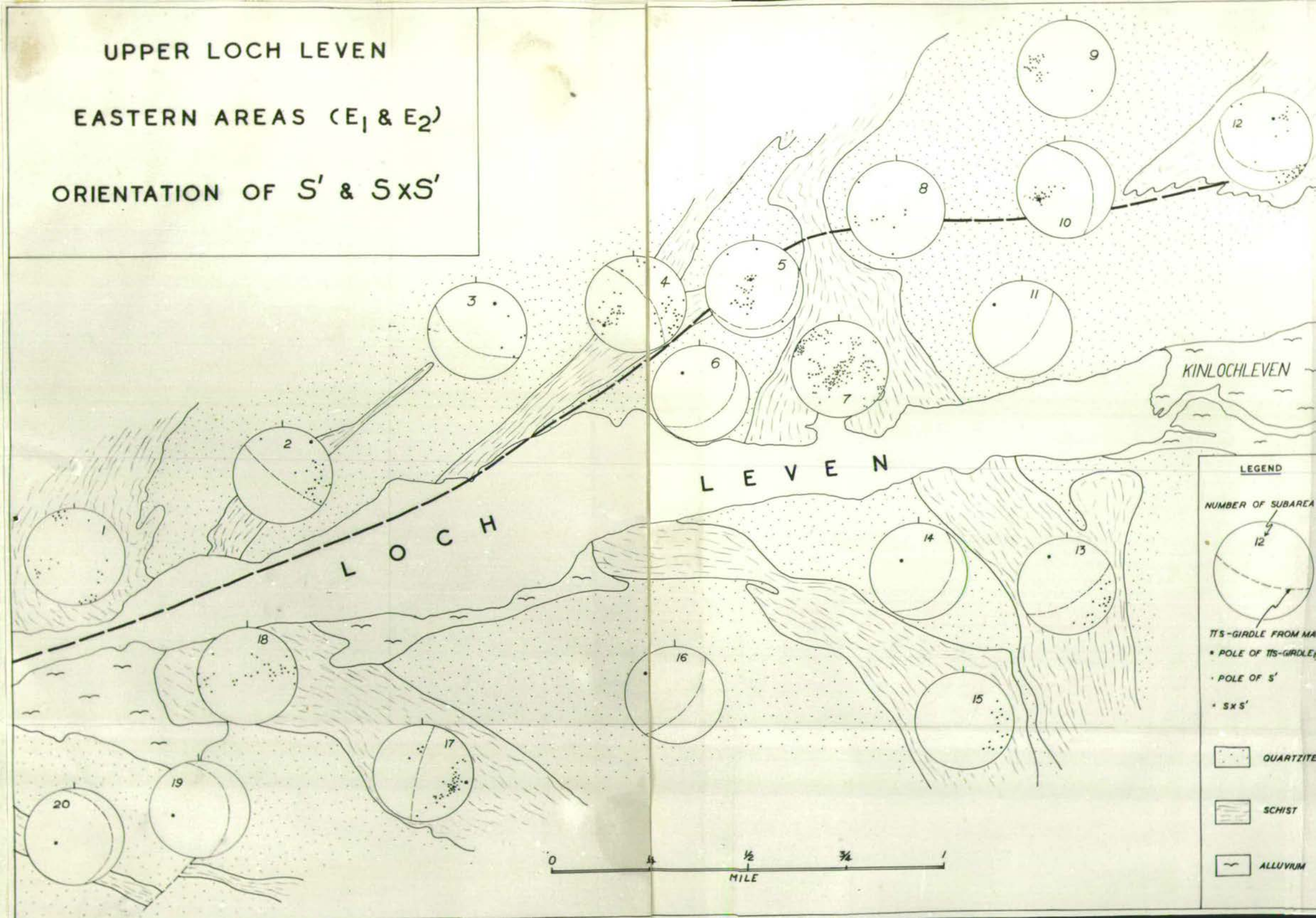


Map 2. Explanation in text.

UPPER LOCH LEVEN

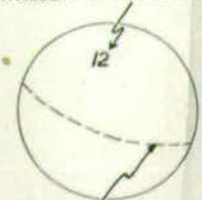
EASTERN AREAS (E_1 & E_2)

ORIENTATION OF S' & $S \times S'$



LEGEND

NUMBER OF SUBAREA



TTS-GIRDLE FROM MAP

• POLE OF TTS-GIRDLE

• POLE OF S'

• $S \times S'$

QUARTZITE

SCHIST

ALLUVIUM

0 1/4 1/2 3/4 1
MILE

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- II. 10. Structural Features of the Rocks of the Moine Thrust-Zone. (Appendix to "The Moine Thrust - its Discovery, Age and Tectonic Significance", by D.B.McIntyre - jointly with D.B.McIntyre and J.M.Christie)

With the Authors' Compliments.

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APPENDIX

by JOHN M. CHRISTIE, DONALD B. MCINTYRE AND L. E. WEISS

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THE VIEWS EXPRESSED in the paper were reached after a detailed study of the literature, and were greatly influenced by the following:

1. The schuppen of the thrust-zone, as shown in the published sections, define a *B*-axis trending NNE.-SSW.
2. Frequent references in the literature to lineations in *a*.
3. The author's observation at Glen Coul of *B*-structures trending NNE.-SSW.
4. The author's observation at Knockan and Eriboll of brecciation along the thrust.

It is stated in the paper that 'the tectonics of the mylonite-zone have never been adequately described, but an investigation which promises to fill this gap has now begun'. After the paper was written, one of us (J.M.C.) spent several months in Assynt studying the structures related to the thrusts. As a result of that work and of subsequent laboratory study of the specimens collected, it was discovered that the lineations in the mylonite-zone, previously taken to be *a*-structures giving the direction of thrusting (e.g. Bailey, *Geol. Mag.*, 1935, 72, p. 158), are in fact *B*-structures intimately connected with the widespread *B*-structures in the Moine Schists to the east. Following from this discovery, we have made a joint study of a number of exposures of the thrusts from Skye to Fair Aird. It need hardly be said that a great deal of further work is required and is proceeding, but the following new facts are so relevant to the present discussion that we feel they should be recorded here.

1. There has been a single penetrative movement about a common *B*-axis in the Moine Schists, the mylonites above the Moine Thrust, and the deformed Lewisian, Torridonian and Cambrian rocks below. The mylonites do not merely constitute the milled-down schists of the Moine Series. The conspicuous *B*-axis in the Moine Schists must have been imprinted in post-Cambrian time.

2. Many of the 'quartz-mylonites' (including certain deformed Cambrian rocks) associated with the Moine Thrust are not true mylonites *sensu stricto* (see Turner, *Mem. Geol. Soc. Amer.*, 30, 1948, pp. 10-11, 201), but have undergone partial, sometimes considerable, re-crystallisation. Re-crystallised quartz-mylonites have also been found to the east of the Great Glen (Weiss, McIntyre & Kürsten, MS. in press).
3. Repeated movement is indicated locally (e.g. at Knockan, Loch an Nid, Loch Ailsh and Loch Hope) by brecciation, movement on joints, and even mylonitisation of the older mylonites of the Moine Thrust. An upward age-limit for these movements has not yet been determined.
4. At some localities, notably the Knockan Crag and Loch an Nid, the Moine Thrust-plane is a clean break separating rocks of different composition; but elsewhere (e.g. at Stack of Glencoul) it is represented by a movement-horizon of considerable thickness in which Moine and Cambrian rocks are both involved. Yet again (e.g. at Allt nan Earbagan) it is in places possible to map a thrust-plane on the basis of lithological differences, although the rocks both above and below are tectonites with similar fabrics.
5. Sedimentary structures have been reported from several localities in the Moine Schists. In Strath Oyckell the structures, which look like current-bedding, can frequently be seen to be tautozonal about the *B*-axis. It may be that the structures are indeed of sedimentary origin, but, if so, only those of a particular orientation have been preserved (cf. Green, *Quart. Journ. Geol. Soc. Lond.*, 1931, 87, p. 529).
6. The symmetry of the fabric both of the Moine Schists and of the rocks intimately associated with the thrust seems to be characteristically nearly orthorhombic. The association of these fabrics with large-scale transfer of Moine over Cambrian raises fresh problems.

DISCUSSION

MR. J. M. CHRISTIE pointed out that too much importance may have been attached to the imbricate zones in attempts to determine the direction and sense of movement of the Moine and underlying nappes. In the field, the schuppen-structure is seen only as a repetition of stratigraphic horizons, and the orientations of the intervening thrusts are usually difficult to determine. The speaker had stratum-contoured the major thrusts as shown on the Geological Survey One Inch Sheets, and he had found that the intersections of the thrusts gave a strong maximum indicating an axis of intersection or flexing plunging at 10-20° to N. 100° E. This β -diagram was exhibited. The speaker also exhibited quartz-fabric diagrams of strongly lineated Cambrian quartzites from the thrust-zone showing *B*-axes plunging at low angles to N. 100-120° E.

DR. GILBERT WILSON congratulated Dr. McIntyre on his most interesting and useful review of the story of the Moine Thrust, and on the work he had done in checking the evidence upon which the age of the dislocation had been based. Like Francis Bacon's acquaintance, however, the author had '... put that which was most material in the postscript ...', and left not only the speaker, but probably many others in the room wondering where we went from here! The information given by Dr. McIntyre, that he and Mr. John Christie, working in the Assynt region, have found structures in the mylonites and in the Cambrian rocks of the zone of dislocation, which are co-linear with the south-eastward plunging, minor structures in the Moine Schists themselves, is of the greatest importance, but one wonders what is its significance. Does it mean that the movements in the thrust-zone were lateral, normal to these *B*-axes which were briefly mentioned; could these *B*-axes of symmetry be parallel to the direction of tectonic transport, as was suggested by E. M. Anderson in 1948 (*Quart. Journ. Geol. Soc.*

Lond., 104, p. 90), by A. Kvale in 1953 (*Quart. Journ. Geol. Soc. Lond.*, 109, p. 51), and by R. Balk in 1952 (*Journ. Geol.*, 60, p. 415); or are we faced with the possibility that the minor structures, lineations, mullions and the like, of the Moine Series and of the Moine Thrust Zone have really only minor significance? One is reminded of Wegmann's warnings that the magnitudes or scales upon which structures occur in the field must be taken into consideration when assessing their tectonic importance.

Dr. Wilson said that he realised that the facts were still being gathered, but the brief summary of them outlined this evening whetted one's appetite for the final conclusions of Mr. Christie's investigations in Assynt. It will be particularly interesting to compare them with those of Mr. Peter Wilkinson, from the Loch Eriboll area, and of Mr. M. R. W. Johnson, who is studying the same general problems in the ground between Loch Kishorn, Loch Carron, and north of Achnashellach, in Wester-Ross.

DR. J. SUTTON congratulated Dr. McIntyre on an absorbing paper. It was well worth tracing back accepted ideas on Highland geology to the circumstances in which they originated. The speaker believed that much of the growth of the concept of Lewisian inliers came about because the surveyors, fresh from their triumphs in the belt of dislocation, carried ideas developed there eastward into the folded crystalline schists.

Geological myths were not confined to the past, however. He thought there was probably one depicted on the blackboard tonight where Dr. McIntyre had shown the Moine fold-trend as running from NW. to SE. The speaker thought this quite erroneous. The notion was apparently supported by the existence of certain folds, such as those at Fannich and Strath Oykell, which ran in that direction, and by observations that lineations and the Moine petrofabric *B*-axes plunged into the south-eastern quadrant in many localities. The picture changed when every structure over an extensive area was examined. The speaker and Dr. Watson had examined an area in Ross-shire where one third of the all south-easterly plunging lineations noted by Dr. Coles Phillips in the Moines, were located (fig. 5 of Coles Phillips, *Quart. Journ. Geol. Soc. Lond.*, 1937, 92). They had found a considerable variation in the trend of the linear structures and of the folds. This suggested that an adequate sample of the lineations might not yet have been obtained in other Moine areas.

Secondly they had found that the nature of the major folds could not be deduced with confidence from the small axial structures alone. There were several possible relationships between small and large structures which they had noted in Ross-shire. The linear structures frequently ran parallel to the nearest fold-axis. Sometimes, however, a fold was accompanied by few or no linear structures. Elsewhere the linear structures reflected the interaction of two differently directed folds. Particularly striking examples of this had been found near Loch Monar by Mr. Ramsay.

The Moine folds in Ross-shire ran in a number of directions and appeared on the whole to indicate a westerly or west-north-westerly movement of the overlying beds relative to those below. The classical view on movement in the folded Moines and Coles Phillips petrofabric work could be reconciled and both shown to be substantially correct in Western Ross.

He thought this was worth bearing in mind before reorienting the accepted directions of movement in the thrust-belt in the light of the important new observations made by Mr. Christie. He enquired if the small structures could be related to the large displacements, such as those indicated by the well-known thrust-slice containing rocks identical with those seen in the Foreland near Loch Laxford.

DR. L. E. WEISS noted that the statement in the appendix, that a common *B*-axis exists in the Moines, mylonites and other rocks of the thrust-zone, has at once raised the question of the movements which have affected these rocks. Dr. Sutton suggested that this statement implies a reorienting of the accepted directions of movement in the thrust-belt; the speaker suggested that to look for a *direction of movement* in either the Moines or the mylonites is, at the moment, premature, since it has not yet been established whether the penetrative movements which have occurred in these rocks were of a symmetry and style which can be described in terms of one, two or, indeed, any *directions of movement*. The continual search for a single direction of movement or

transport to explain the complexities of the Moine and associated rocks has led to much futile controversy. Dr. Kvale has used the term to describe a direction of extension in a rock-mass, and he has equated this with the believed direction of discontinuous movement on nearby thrust-faults. Consequently he had to reject fabric-symmetry as a guide to symmetry of movement. The example of the quartzite discussed by Dr. Balk, also cited by Dr. Wilson, is one in which under-emphasis of fabric-symmetry has complicated what may be a simple picture. The symmetry of Dr. Balk's diagrams agrees, for the most part, with the symmetry of the movements he suggests.

Since in several localities the Moines rest on top of Cambrian rocks, we are justified in saying that at some period in the history of the thrust-belt there have been large-scale discontinuous movements, probably with monoclinic symmetry. It does not follow that the fabrics we now see in these rocks were produced by and reflect the symmetry of these discontinuous movements. Indeed, the widespread orthorhombic symmetry of fabric (and thus of the *last* penetrative movements in the rocks), observed by Mr. Christie in the thrust-zone, suggests otherwise. Yet to be established is the chronology of penetrative movement, 'thrusting' and crystallisation. Once this has been done, we shall be in a better position to discuss direction and sense of translation, axes of rotation and directions of elongation and shortening in the rocks of the thrust-belt.

MR. P. WILKINSON, in welcoming the paper, wished to take the opportunity of correcting a possible misunderstanding which had arisen from a contribution made to the discussion of Dr. G. Wilson's paper on mullion and rodding structures (*Proc. Geol. Assoc.*, 1953, 64, p. 145). On the ground east of Loch Eriboll, visible lineations, including quartz-rodding, as described by Dr. G. Wilson, were to be found in quartzites (and to a much lesser extent in quartz-chlorite-sericite schists and sheared Lewisian gneisses) of the Eriboll Nappe. These were described as lineations in *B*. These rocks lie beneath a thrust which separates them from presumed Moine siliceous granulites. Stereographic plotting of macro-lineations shows the Eriboll and Moine Nappes to have homologous fabrics. The ambiguous statement mentioned above apparently led Dr. Wilson to believe that the speaker's belief in a *B*-lineation in rocks close to the thrust was based on comparison of fabric with known *B*-lineations in Moine rocks—actually the reverse of the true situation. This result is in harmony with the findings described by Dr. McIntyre.

Another point, which has been the cause of a great deal of confusion of thought in Highland geology, was the varying usage of the term mylonite. The term had been coined by Lapworth and rigidly and clearly defined by him (*Nature*, 1885, p. 559) with reference to the rocks of the Eriboll region. Unfortunately no type-locality was nominated and his field-notes and maps appear to be of no assistance in this connection. The rocks of the speaker's Eriboll Nappe, i.e. rocks lying between the Eriboll Thrust (?Moine Thrust of Peach & Horne) and the higher Moine Thrust (unnamed by Peach & Horne, above which lie siliceous granulites of presumed Moine age) had been mapped by Peach & Horne on Sheet 114 variously as quartz-schist, 'crush-rocks', frilled schist, schistose marble, and 'thrust' Archaean gneiss. The same tectonic unit, traced south on to Sheet 108, is mapped as 'Mylonised Rocks and Green Schists above Moine Thrust Plane' and on the Assynt Sheet as 'Mylonised Rocks'. The common practice seems to be to refer to all these as mylonites. This is unfortunate as it is often thought to imply that cataclastic structures predominate and hence that thrusting took place in cold rocks. In fact, rocks of the Eriboll Nappe are extensively recrystallised and conform more to Lapworth's definition of 'augen schists'. This accorded with A. G. MacGregor's view (*Trans. Edinb. Geol. Soc.*, 1952, p. 241 *et seq.*) that the Moine rocks were 'hot' when thrusting took place. Further evidence supporting this view was the discovery of apparently syntectonically crystallised green tourmaline in rocks of the Eriboll and Moine Nappes. True mylonites were to be found, but were surprisingly rare, and late movements had been present in the cooling or cold rocks and had resulted in folding and rucking of lineations, faults dislocating the thrust-planes, and local cataclasis. The problem was emphasised by the presence of quartz-chlorite-sericite schists, identical with those in the Eriboll Nappe, well back in the Moine Nappe. Indeed, Cadell had recorded 'Eriboll Schists' in the west face of Ben Hope, four miles east of the main dislocation (*Central Sutherland Mem.*, p. 29).

DR. MCINTYRE, in his reply, said that Dr. Wilson and Dr. Sutton appeared to suppose that he ascribed all importance to minor structures. This was quite wrong; in all his papers on Highland structures the author, as a pupil of Wegmann, had emphasised the scale or scales on which the structures being discussed were displayed, and he had pointed out the necessity for information on as wide a variety of scales as possible. In the present instance, Mr. Christie had presented data ranging from the scale of the thin-section to that of the one-inch map; no wider range of scales was as yet possible. The author (*Geol. Mag.*, 1950, **87**, p. 428) had listed the ways known to him for the determination of the axial-plunge of the grand-scale structures. He wondered how Dr. Sutton and Dr. Watson determined the form of the major folds.

Dr. Sutton was referred to the author's note (*Geol. Mag.*, 1951, **88**, pp. 150-1) on the complex pattern of the fold-trends in the Highlands and to the reference therein to the special interest of the Loch Monar area. Dr. McIntyre had been privileged that afternoon to see some of the results of Mr. Ramsay's work at Loch Monar which, when completed, would undoubtedly prove to be of great importance. In 1951 the author had urged the need for further work on lineations in the Highlands, and he welcomed Dr. Sutton's and Dr. Watson's work in this field. He wished to stress the necessity for the correct identification of *B*-lineations, since the possibility of confusion with axes of internal rotation seemed to be real.

Dr. Sutton's final remark presumably referred to the displacement of the Laxford-Stack line. The author pointed out that, previously, this had been used to give an estimate of the amount of travel of the Glen Coul nappe on the assumption of a north-westward direction. A clear account of the argument had been given by Sir Edward Bailey (*Geol. Mag.*, 1935, **72**, p. 158). Dr. McIntyre thought that Dr. Weiss's remarks on direction and sense of movement were particularly timely, and he wished to express wholehearted agreement with them.

It was especially gratifying to find that Mr. Wilkinson's detailed work in Eriboll had led him to conclusions so similar to those put forward in the appendix. The full results of his investigation were awaited with interest. Dr. Wilson had asked where we went from here. Since Dr. McIntyre was shortly leaving for California, he said that he would watch with keen interest the progress of research on the fascinating and difficult structures of the Highlands.